2017 ASHRAE STUDENT DESIGN COMPETITION

HVAC SYSTEM SELECTION

Warsaw University of Technology PRESENTS

PROJECT ISLAND

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Table of Contents

List of Tables

List of Figures

1 EXECUTIVE SUMMARY

The purpose of this report is to present the system selection process of a heating, ventilation and air-conditioning system for a new single-story government meteorological and housing building in the Diego Ramirez Islands (Islas Diego Ramirez) in Chile, South America. The final HVAC System Selection and Design for the proposed building shall address the following major design goals:

- Low Life Cycle Cost
- Low Environmental Impact
- Comfort and Health
- Creative High Performance Green Design
- Synergy (with architecture)

The Owner's budget for the project is $4,6 million. Building's considered life cycle is 50 years. In Project Island 3% inflation rate and 4% return of investments were taken into consideration.

Architecture drawings were delivered along with Owner's Project Requirements, Utility and Service Overview and Weather Data.

The team created BIM model using Autodesk Revit. Model contained parametric information about the building, which was used for calculations and simulations.

The indoor design conditions were determined by the owner and ASHRAE Standards. Team decided to partially change these conditions and appropriate justification is included. Compliance with ASHRAE 55 is ensured.

Along with computer calculations team performed manual calculations of heating and cooling loads based on ASHRAE Fundamentals and ventilation rates from ASHRAE 62.1

To determine building loads and system energy usage, team exported BIM model to IES Virtual Environment software. Then all systems were simulated in a dynamic way, with a 1 hour time step.

According to ASHRAE 90.1 Appendix G the team simulated baseline system with Packaged Rooftop Air Conditioner (PSZ AC) with a Fossil Fuel Furnace. Rooms were heated with air prepared by gas furnace unit. Air was humidified by duct steam humidifier where steam was generated by gas boiler. Hot air was distributed by wall and underfloor diffusers. In some rooms team decided to design direct vent gas furnaces due to low heating loads. Gas storage water heater was applied to produce domestic hot water.

For the proposed design, the team considered three HVAC system options:

- **WSHP** (Water Source Heat Pump)
- **GHP&CB** (Gas Heat Pump & Condensing Boiler)
- **WERH** (Wind Energy Radiant Heating)

The systems' operation was modeled in actual weather conditions. Factors like Life Cycle Cost, energy usage, sustainability or environmental impact were considered. Design options were judged with a multi-criteria analysis, that included grading with LEED v4 rating system. Finally, the first option – **Wind Energy Radiant Heating** was chosen to be the best solution for the given building. Proper justification for this decision choice is presented in a following report.

Figure 1 – LEED v4 Certified

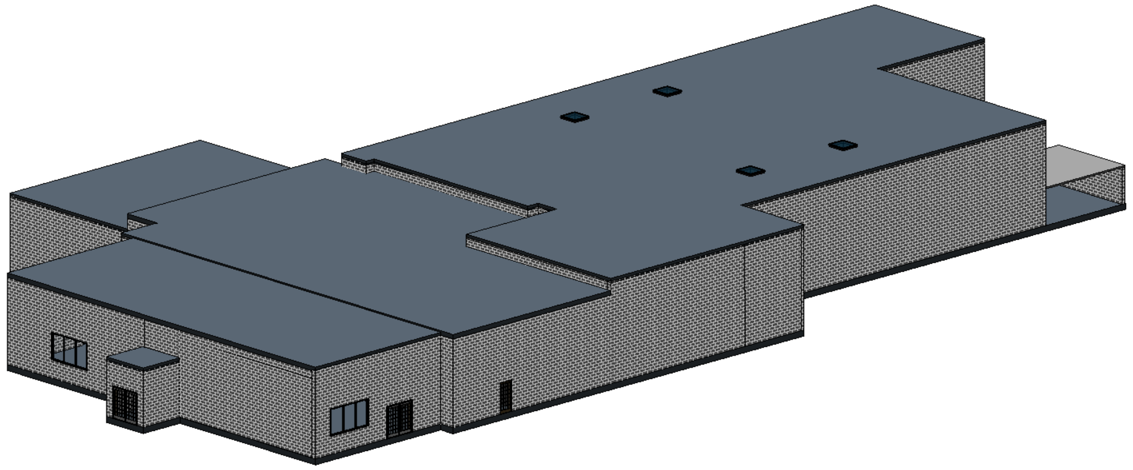


Figure 2 - BIM 3D Building Model

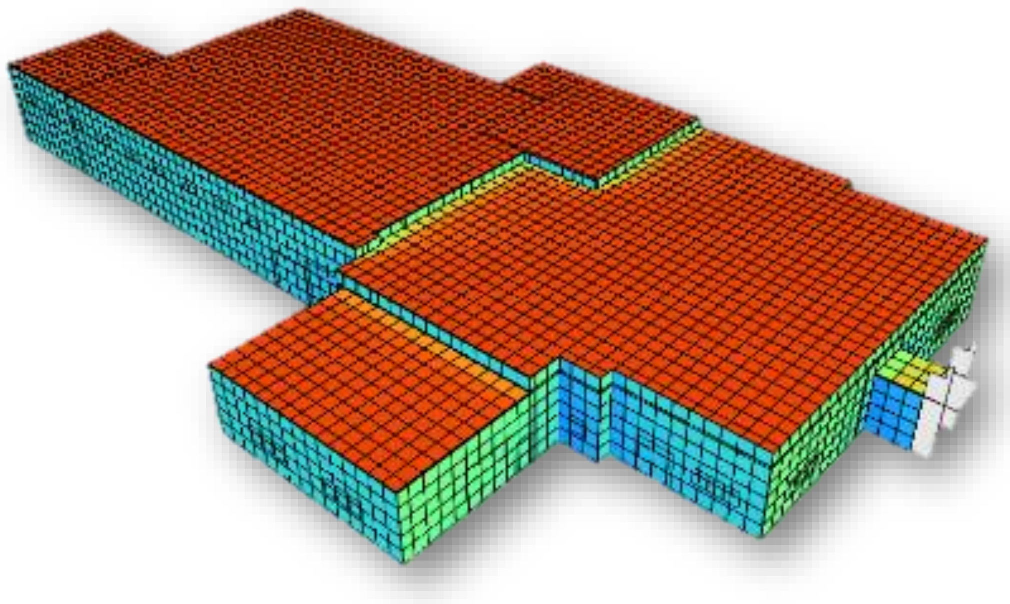


Figure 3 - IES Building Model

2 INTRODUCTION

2.1 Localization

Figure 4 – Building location

Figure 5 – Rockhopper penguin

A building is located in Chile, on one of *Diego Ramirez Islands* - a small group of islands located near Cape Horn. *Isla Gonzalo* is the biggest one, approximately 0,05 square miles. This is the southernmost inhabited outpost of South America. The islands are known for being an important nesting site for a number of southern seabirds, including albatrosses and penguins. Rockhopper penguin

2.2 BUILDING DESCRIPTION

A new Meteorological Station is a single-story government, meteorological and housing building. The building first floor and mezzanine is approximately 19,000 square feet and includes following main types of rooms:

- Dwelling units - 8 bedrooms, community room, kitchen, etc.
- Work & studying areas - office, conference room, learning center, quiet room.
- Meteorological station - located above office, on mezzanine
- Car service areas: large car service hall with stalls for repairing vehicles, car wash and a small garage

2.3 OWNER'S PROJECT REQUIREMENTS

The Owner's Project Requirements include:

→ Owner's Directives:
- comply with and exceed energy conservation requirements as stated in ASHRAE 189.1
- low utility and maintenance costs of installed systems
- excellent indoor environmental quality which meets ASHRAE 62.1 and ASHRAE 55
- superior acoustic criteria

→ Design Requirements
- HVAC System selected upon Owner's design criteria which include room occupancy, interior conditions and sound

→ Budget Considerations and Limitations
- Budget: USD$200/sqft
- Life of the building: 50 years
- Return on investment: 4%
- Inflation Rate: 3%
- Utilities: water, natural gas, propane, electricity, sewage

→ Building Assumptions
- Window Data: Double glazed, fixed windows, ½" air space, low emissivity coating on third surface, bronze tint.
- Wall Data: Masonry mass wall construction, light tan color limestone.
- Roof Data: Insulation over concrete deck.
- Floor Data: Concrete poured as slab on grade.

→ Codes and Standards
- International Building Code. Design Teams should assume the IBC as the governing Code for the Competition.
- ASHRAE Standard 15, current version
- ASHRAE Standard 55, current version
- ASHRAE Standard 62.1, current version
- ASHRAE Standard 90.1, current version
- ASHRAE Standard 154, if applicable current version
- ASHRAE Standard 189.1, current version
- ASHRAE Handbooks, current versions
- Industrial Ventilation, Manual of Recommended Practice.

2.4 BUILDING ENVELOPE

According to ASHRAE Standard 90.1 Table B1-3 the building is located in Zone 6A - Cold Humid. Building envelope construction and all insulation values meet standard minimum values from the ASHRAE 189.1 Table E6.

Element	Description	U-Value
External Wall	8" Masonry Mass Wall	0,069
External Window	Low-E, Double Glazing, bronze tint	0,290
Ground/Exposed Floor	Concrete poured as slab on grade	0,045
Roof	Insulation entirely over concrete deck	0,029
Door for vehicle access	Metal, insulated door	0,440

Table 1 - Assumed U-Values for building envelope

According to ASHRAE-90.1 Chapter 5.4 air leakage values were considered to calculate infiltration of doors, windows and skylights.

2.5 LIGHTING

Lighting power density LPD assumed was based on ASHRAE Standard 90.1-2016 Section 9 for a range of space types.

Typical office space LPD are as follows:

- Office 0,82 W/ft^2
- Garage 0,80 W/ft^2
- Dormitory-Bedroom 0,52 W/ft^2

2.6 UTILITIES

All the values come from "2017 Student Design Competition: Utility and Service Life Overview", except natural gas escalation rate which was based on 10-year average increase for utility provider in the US.

ELECTRICITY			NATURAL GAS			WATER AND SEWER		
"On Peak Cost"	0,1614	$/kWh	Cost	7,91	$/Mcf	Water	0,02	$/cf
"Off Peak Cost"	0,085	$/kWh	Annual Increase	3	%	Sewer	0,003	$/gal
Peak Demand Cost	9,75	$/kWh				Annual Increase	2,5	%
Inflation Rate	3,5	%						

Table 2 - Utilities costs

3 WEATHER DATA

3.1 DRY-BULB TEMPERATURE (DBT)

Figure 5 presents dry bulb temperature in a typical year on Diego Ramirez Islands. It was assumed that there is no clear boundary between summer and winter. DBT passes through the freezing point of water multiple times which can cause internal condensation, moisture trapped in the wall constructions will experience a daily freeze-thaw cycle that can degrade wall integrity and effective R-values.

Below are presented some characteristic temperature values:

Highest dry-bulb temperature	66,2 ˚F	01.29, 13:00
Lowest dry-bulb temperature	14,4 ˚F	07.28, 18:00
Mean dry-bulb temperature	40,8 ˚F	Annual
Amplitude of dry-bulb temperature	51,8 ˚F	Annual

Table 3 - Characteristic Temperature Values, data from Typical Year Weather File

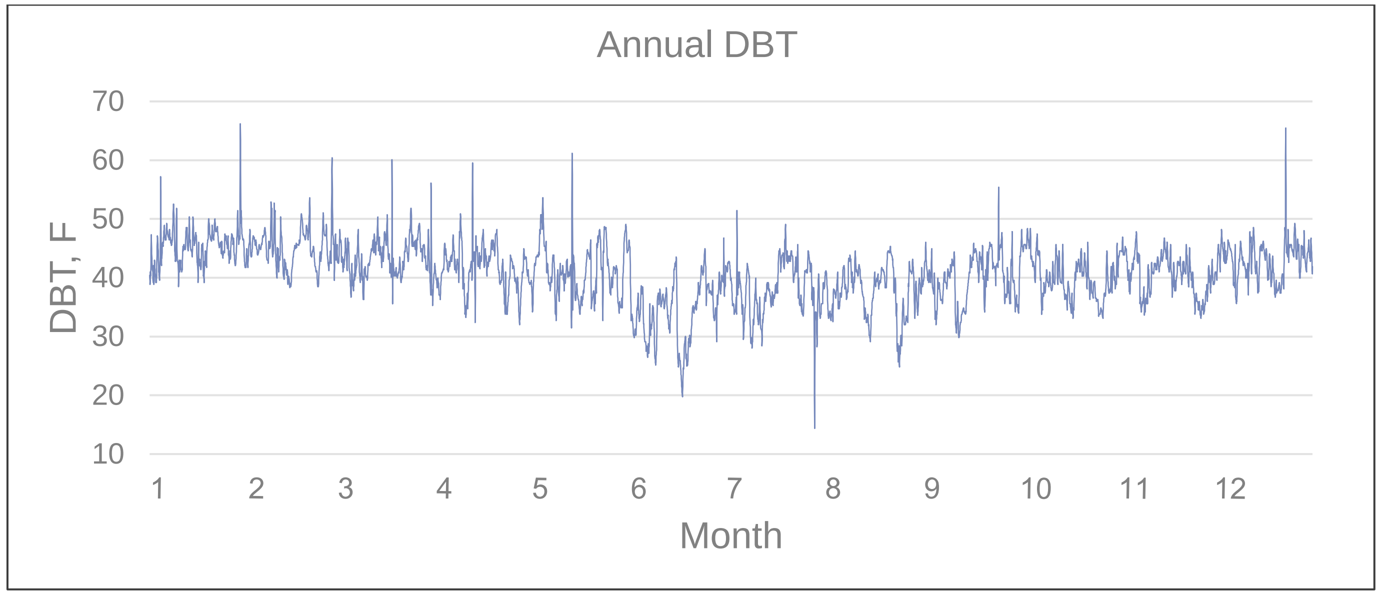


Figure 6 - Annual DBT, data from Typical Year Weather File

3.2 WIND SPEED

American Wind Energy Association recommends applying wind turbines when wind speed reaches 6-9 miles per hour. Wind turbines must stop working when the wind speed is higher than 45 miles per hour to prevent equipment damage. Figure 7 shows Wind Speed histogram with wind speed frequency.

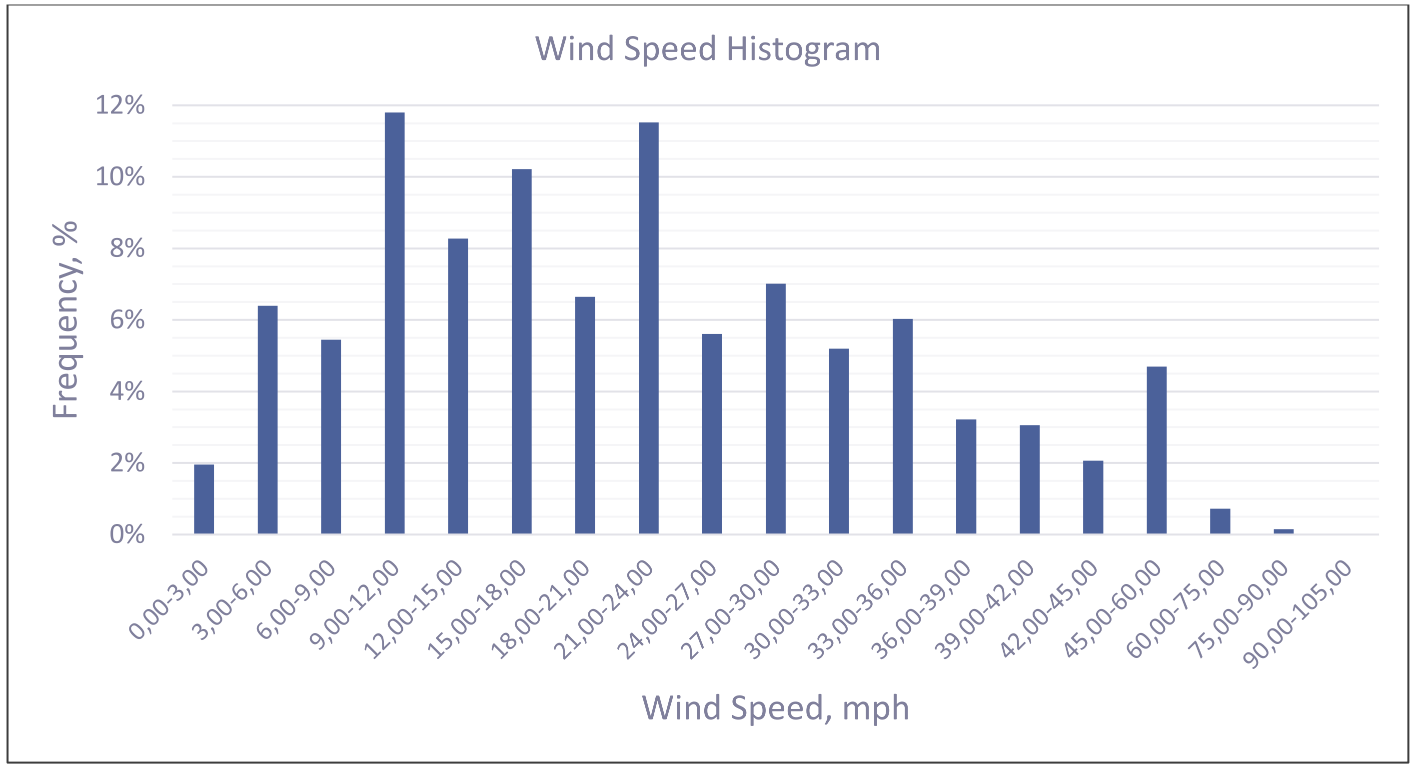


Figure 7 - Wind Speed Histogram, data from Typical Year Weather File

3.3 WIND DIRECTION

Wind direction wheel presents wind direction percentage. Wind direction is mainly W and NW.

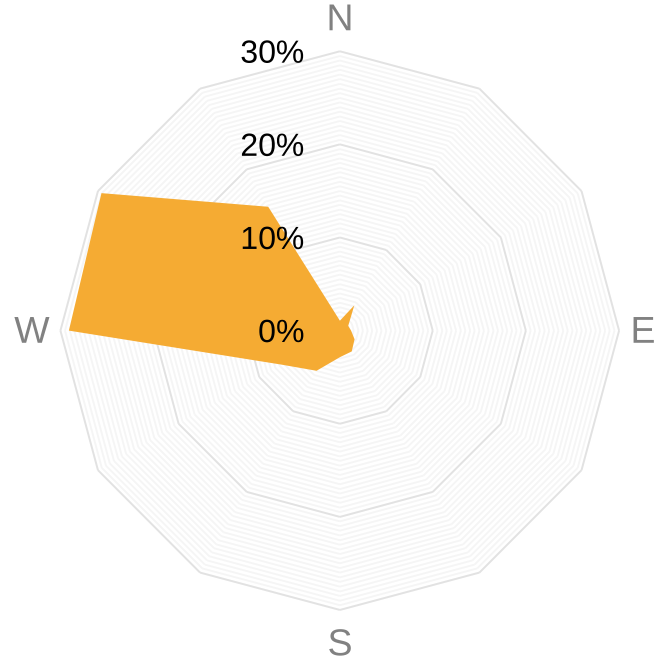


Figure 8 - Wind Direction Wheel

3.4 GLOBAL RADIATION

Global radiation is a sum of direct and diffuse radiation. Following figure presents global radiation values per typical year.

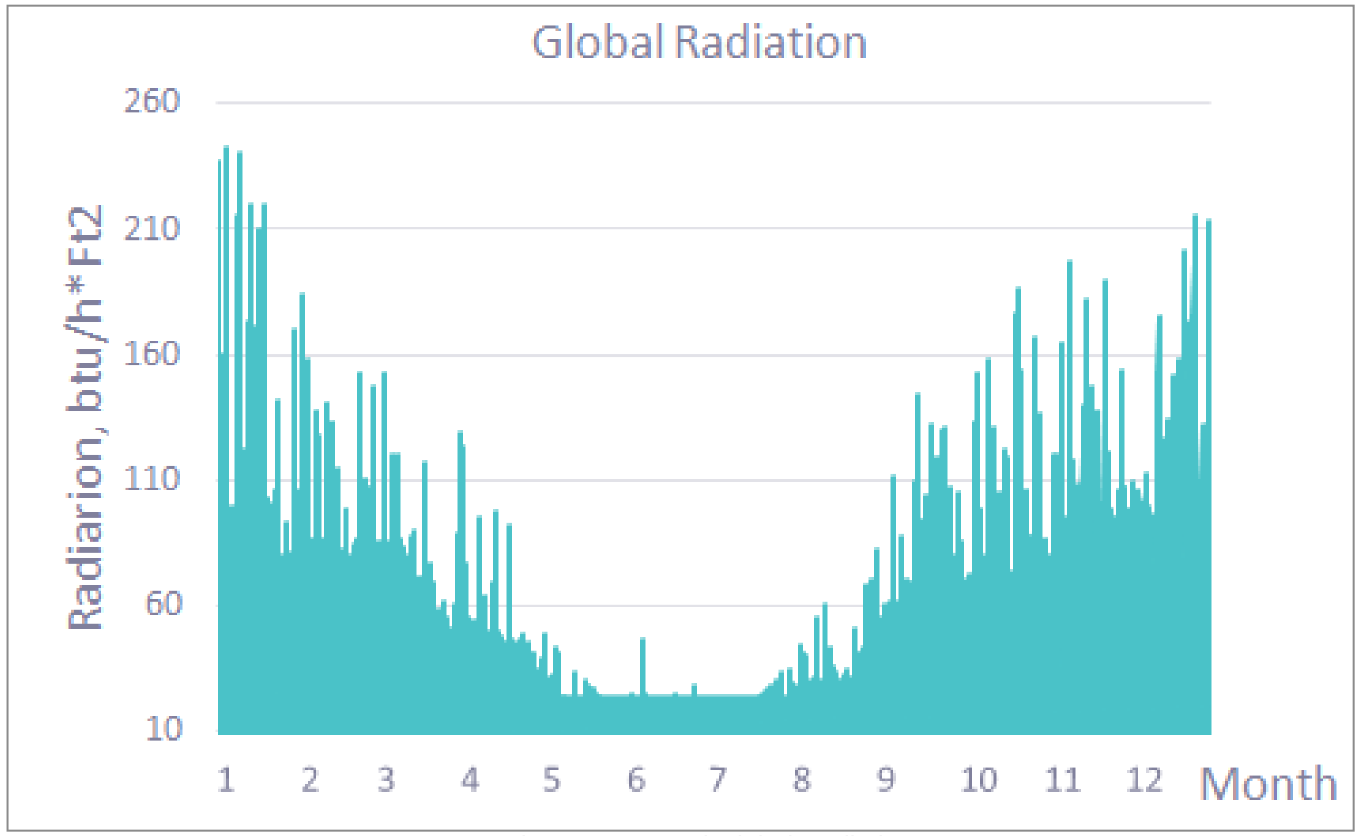


Figure 9 - Annual Global Radiation

From May to August there is lower radiation, due to solar altitude and greater cloudiness.

IES VE software allowed the team to visualize the amount of solar energy transferred to external surfaces of the building during year. The following figure shows an example of a generated analysis result.

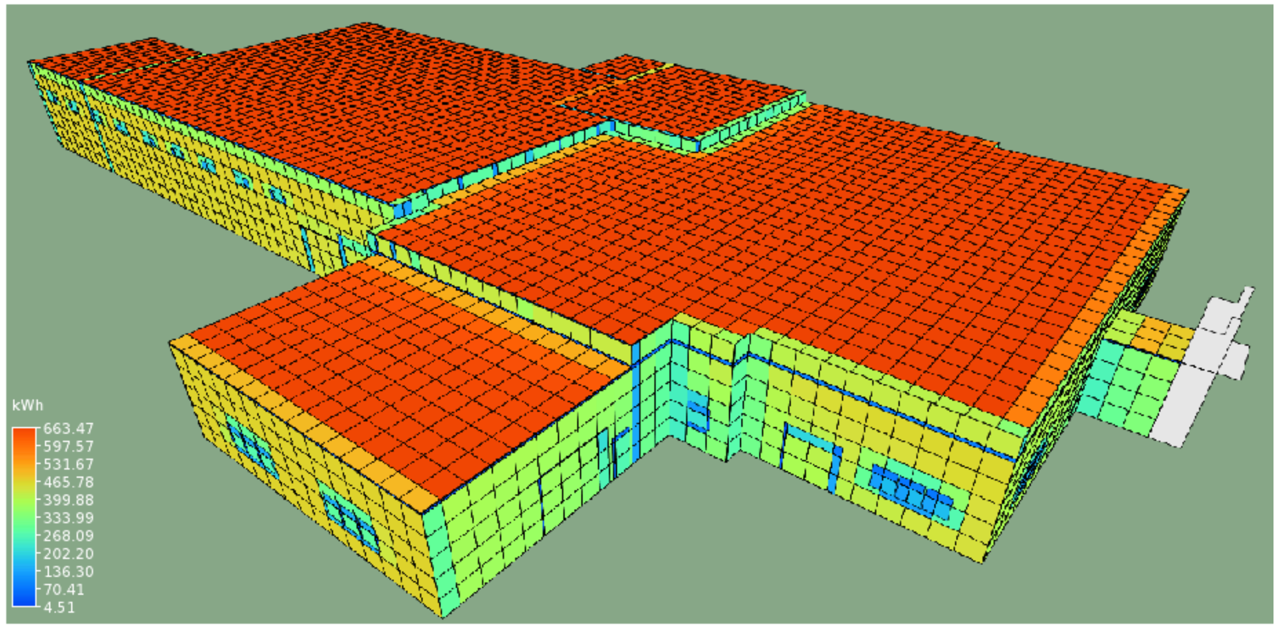


Figure 10 - IES 3D Building Model

3.5 INTERIOR DESIGN CONDITIONS

Interior design temperature setpoints were defined in accordance with Owner's Project Requirements and 2013 ASHRAE Handbook – Fundamentals.

Owner's Project Requirements suggests that interior design temperature should depend on a season of the year - in summer it should be 73°F and in winter 70°F. However, because of rather unvarying outdoor temperature values, the team assumed that dividing a year into separated seasons to specify interior temperature setpoints leads to unnecessary energy consumption.

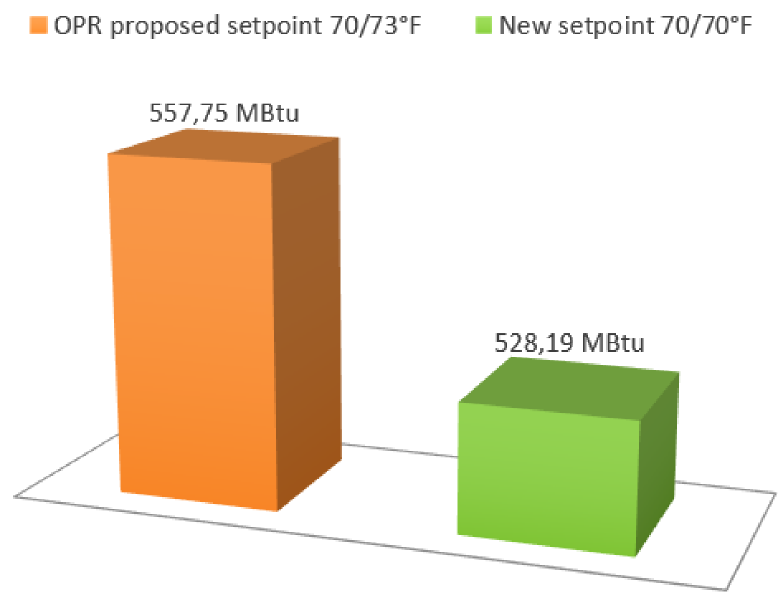


Figure 11 - Yearly heat demand value depending on heating temperature setpoints

We changed the setpoint values from 70°F in winter and 73°F in summer, to a constant value equal 70°F all year long, allows to decrease a heat load value by 29,6 MMBtu, which is around 5,6% of building heat demand.

Basing on this conclusion, the team made a decision to change setpoints specified in Owner's Project Requirements.

Additionally, team decided to change a setpoint in Data Center to a value which will comply with the specific system used to cool racks and server blades, which is described in greater detail in Section no. 7.1.

All temperature setpoints used in calculations are presented in the following table:

Room Type:	Heating Setpoint [°F]	RH [%]
Bedroom, Community Room, Conference, Corridors, Data Center, Exercise Area, Kitchen, Laundry, Learning Center, Meteorological Station, Technical Room, Office, Quiet Room, Bathroom, Toilet,	69.8	55
Service Hall, Car Wash, Vehicle Parking	39.2	-
Shipping Area, Vestibule	60.8	-
Data Center	69.8	55

Table 4 - Interior design parameters

4 LOAD CALCULATIONS

For heating and cooling loads calculation team used IES VE software. It allowed running calculations with two different methods. At first, building loads were determined with a Heat Balance Method, based on a static simulation. However, in order to get more information about building performance and energy demand, more detailed analysis has been run. Team made an hourly, dynamic simulation of building performance.

4.1 HEATING LOADS

Annual building heating sensible load peak value is 54 kBtu/h. Peak value occurs during coldest days in year, while car service hall ventilation rate is increased due to car exhaust fumes presence. However, heating sensible load values above 40 kBtu/h occur during 290 hours in whole year. ASHRAE-90.1 approves system unmet load hours up to 300 of the 8760 hours simulated, so team decided to consider **40 kBtu/h** as a heating peak value for the building.

4.2 COOLING LOADS

Building cooling loads are relatively low, comparing to heat demand. In most of rooms there is no need for cooling during all year long. Annual peak value is 21,1 kBtu/h.

Following figure presents values of heating and cooling loads during year:

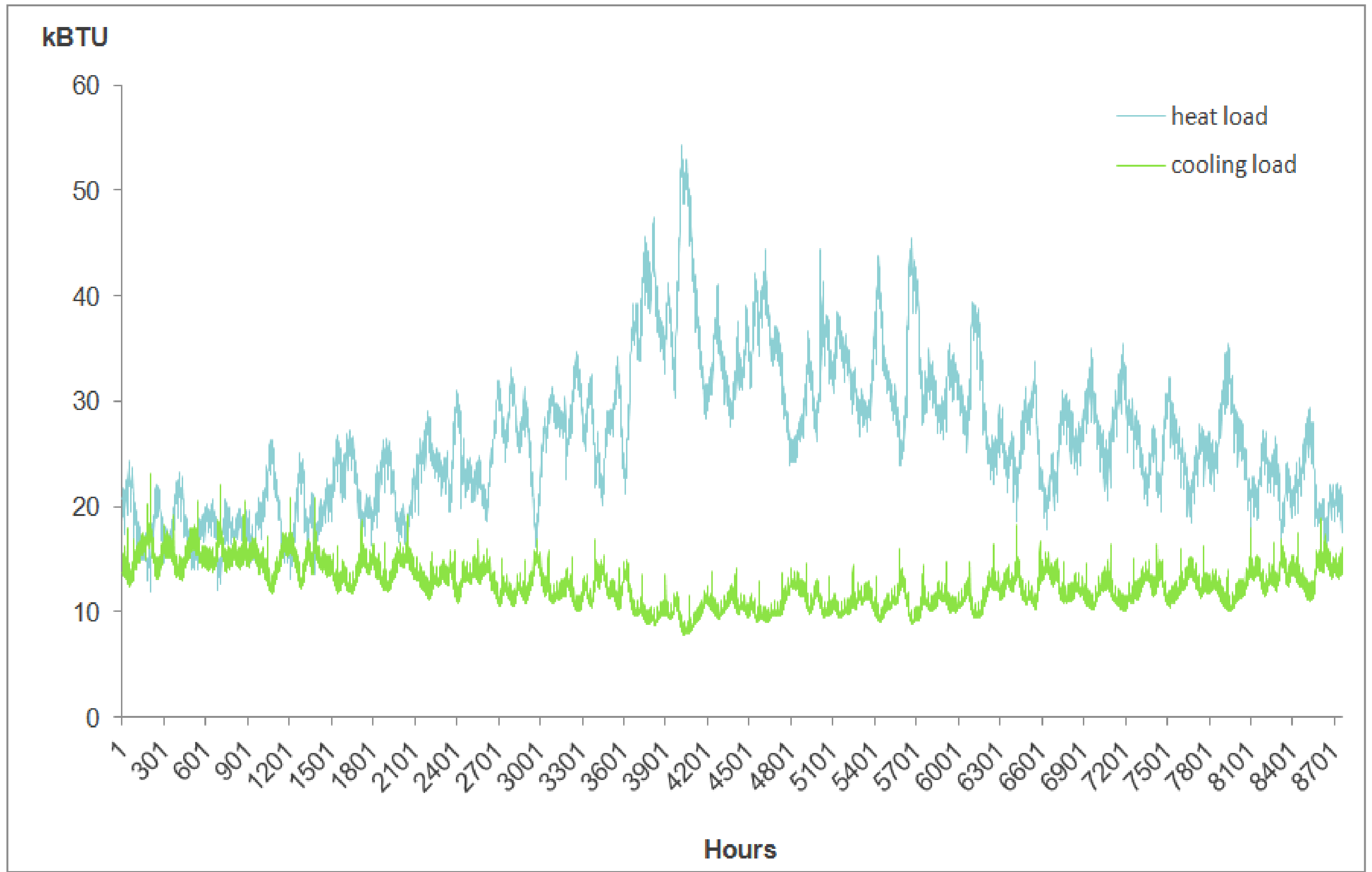


Figure 12 - Heating and Cooling Loads

4.3 SUPPLY AIR HEATING LOADS

Supply air heating loads were calculated with an assumption that supply air temperature is equal to the heating setpoint. So, in most of rooms supply temperature is 70°F all year long. Car service zone has a separate air system and its setpoint is equal 39°F. When an outside air temperature is less than this value, an air heating coil in ventilation system turns on and preheats supply air to this temperature. Also, heat recovery was included in both systems, with 70% and 50% efficiency (in compliance with Standard 90.1 Chapter 6)

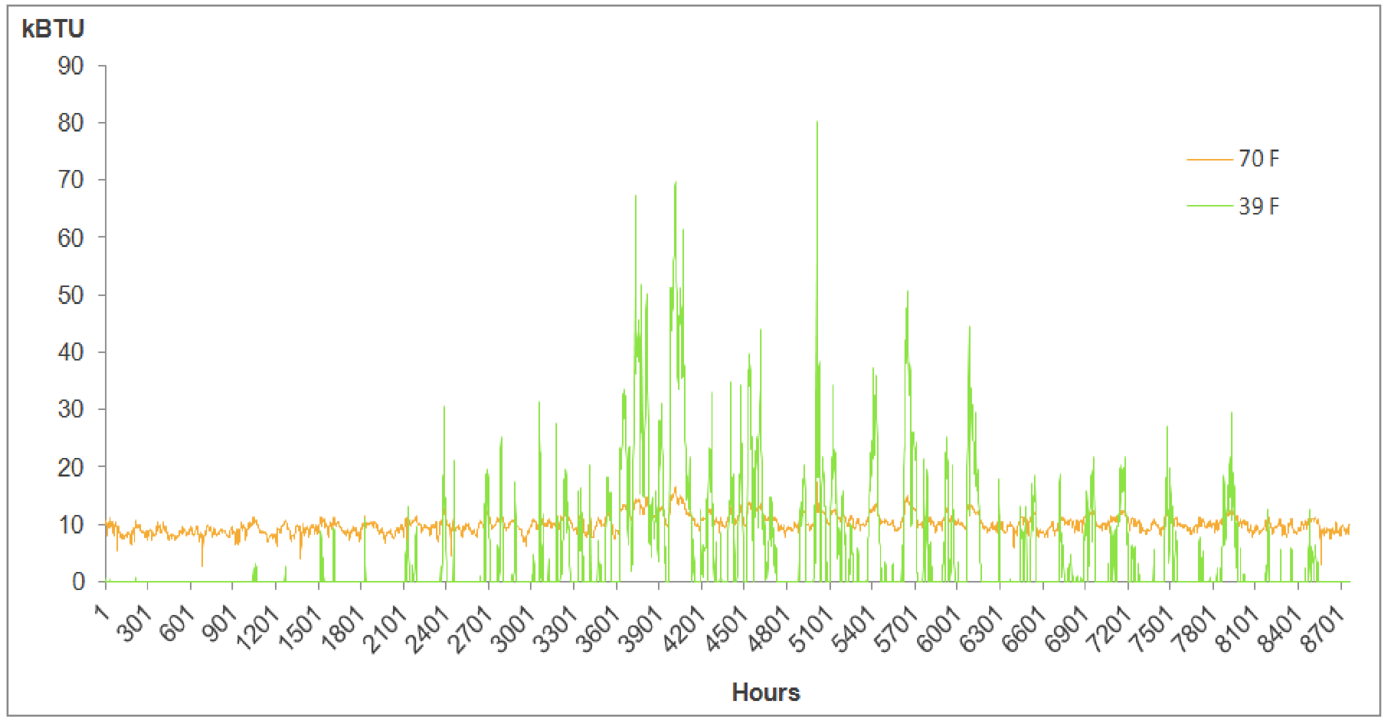


Figure 13 - Supply Air Heating Loads

4.4 HEAT GAINS

4.4.1 Sensible gains

Internal heat is emitted from people, lighting, motors, appliances and equipment. Conduction gains are considered as external and internal. Fenestration is a source of solar gains.

Heat gain rates are considered in accordance with ASHRAE Fundamentals and Owner's Project Requirements. Team created project profiles according to occupancy of each room in 1 hour time interval so all the calculations are based on these variables.

4.4.2 Latent Gains

Latent loads are required to design humidifying equipment in purpose to meet the IAQ design criteria. The main sources of latent gains are people and processes run inside building (e.g. washing cars).

5 SYSTEM DESIGN GOALS

5.1 SUSTAINABILITY

5.1.1 General

Our aim was to design systems that are eco-friendly and efficient. Sustainable building is a design philosophy based on saving natural resources, minimizing human impact on planet and ensure better living conditions for next generations. Sustainability is referred as

> *“Providing for the needs of the present without detracting from the ability to fulfill the needs of the future.”*
> ASHRAE GreenGuide

5.1.2 ASHRAE GreenGuide discussion

The ASHRAE GreenGuide was used to create green and sustainable high performance system design in order to lower environmental impact, and create better environment for the occupants.

5.1.3 Advanced Energy Design Guides discussion

The guide provides prescriptive recommendation packages that are capable of reaching the energy savings target for each climate zone in order to ease the burden of the design and construction of energy-efficient small commercial buildings.

5.2 FLEXIBILITY

Decentralized systems may be very flexible. It means that each space can be precisely conditioned. It saves energy and provides better thermal comfort.

5.3 RELIABILITY

Equipment shall be reliable, which means that every single part should have longer service life and require minimum maintenance.

5.4 MAINTAINABILITY

Decentralized systems generate less problems with replacing and maintenance because equipment is widespread. Also, location is very important. Bad weather conditions can impede maintenance.

5.5 LOW ENVIRONMENTAL IMPACT

5.5.1 Energy usage

The goal of the design is to reduce primary energy usage. It can be fulfilled by using renewable energy sources, rather than fossil based. Moreover, LCC can be reduced by load shifting - accumulating energy in a way it would be used during lower (off-peak) prices occurrence.

5.5.2 Carbon footprint

Improving the energy and carbon footprint of a building and thereby reducing the CO_2 level is inextricably linked to the design, use of materials, construction and operation of the building throughout its life cycle. Carbon footprint is calculated as carbon dioxide equivalent using the relevant 100-year global warming potential (GWP100)

5.5.3 Refrigerants

Environmentally preferred refrigerants have low Global Warming Potential (GWP), provide good efficiency and have low Ozone Depletion Potential (ODP). ASHRAE Standard 15-2013 *Safety Standard for Refrigeration Systems* provides requirements for “safe design, construction, installation and operation of refrigeration systems. During the selection process, the requirements of both section 7.3 and 7.4 affected the placement of equipment and the amount of refrigerant allowed in the building. ASHRAE Standard 34-2013 *Designation and Safety Classification of Refrigerants* also applies to the refrigeration used within a building, and specifically, the volume of refrigerant. In the case of leak, determining the worst-case scenario for the refrigerant dispersed needs to be considered.

5.6 COMFORT AND HEALTH

5.6.1 ASHRAE Standard 62 discussion

ASHRAE-62.1 specifies minimum ventilation rates and other measures intended to provide Indoor Air Quality (IAQ) that is acceptable to human occupants and that minimizes adverse health effects.

Minimum ventilation rates and air classes were found in Table 6.2.2.1 “Minimum Ventilation Rates in Breathing Zone” and minimum exhaust rates were based on Table 6.5 “Minimum Exhaust Rates”.

5.6.2 ASHRAE Standard 55 discussion

ASHRAE-55 defines Acceptable Thermal Environment for General Comfort as PPD less than 10 and PMV Range from -0,5 to 0,5. Calculations approved compliance with ASHRAE-55.

According to ASHRAE-55 Thermal Comfort Guidelines, team specified a representative person. Activity was chosen from Table 5.2.1.2 “Metabolic Rates for Typical Tasks” and Garment Insulation was assumed from Table 5.2.2.2B “Garment Insulation”. Calculations are specified in the following tables:

Activity	Metabolic Rate	
	W/m^2	Met Units
Filing, seated	70	1,2

Table 5- Metabolic Rate

Garment:	I_{cl}, clo
Men’s briefs	0,04
Ankle-length athletic socks	0,02
T-shirt	0,08
Slippers	0,03
Walking trousers (thick)	0,24
Sweater long-sleeve (thick)	0,36
SUM:	**0,77**

Table 6 - Garment Insulation

Due to a fact, that a representative person is sitting on a standard office chair, there was added an insulation value of +0,10 clo.

Finally, team chose a representative person of 1,2 met and 0,88 clo. University of California Berkeley CBE Thermal Comfort Tool for ASHRAE-55 calculated PMV and PPD values. The following psychometric chart shows the results of calculations:

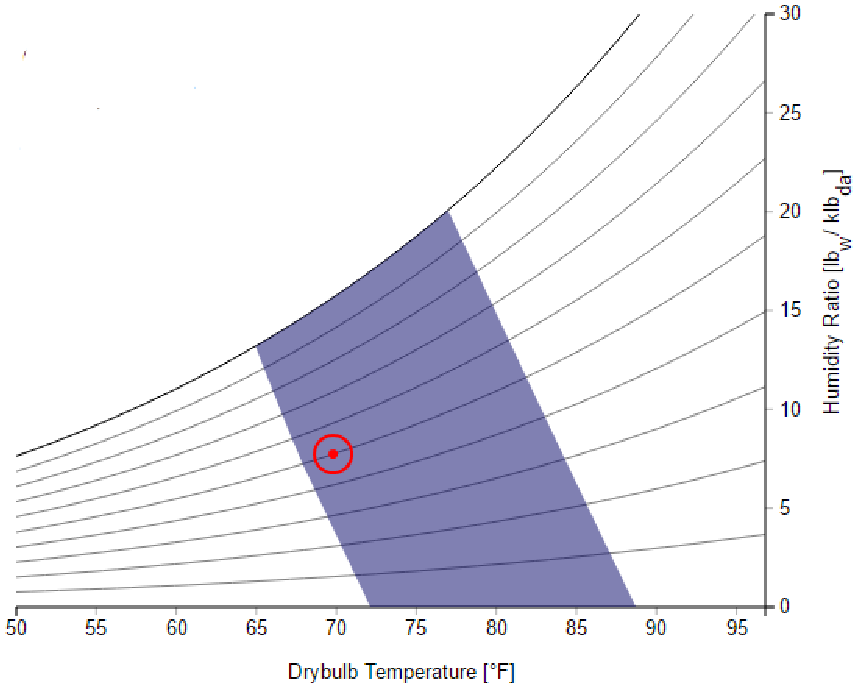


Figure 14 - ASHRAE-55 Thermal Comfort Chart

5.6.3 Zoning/temperature control system

The building was separated into 4 zones, according to a heating setpoint. Setpoint temperatures are described in Chapter 3.5.

Detailed Zone Schema of first floor is presented below:

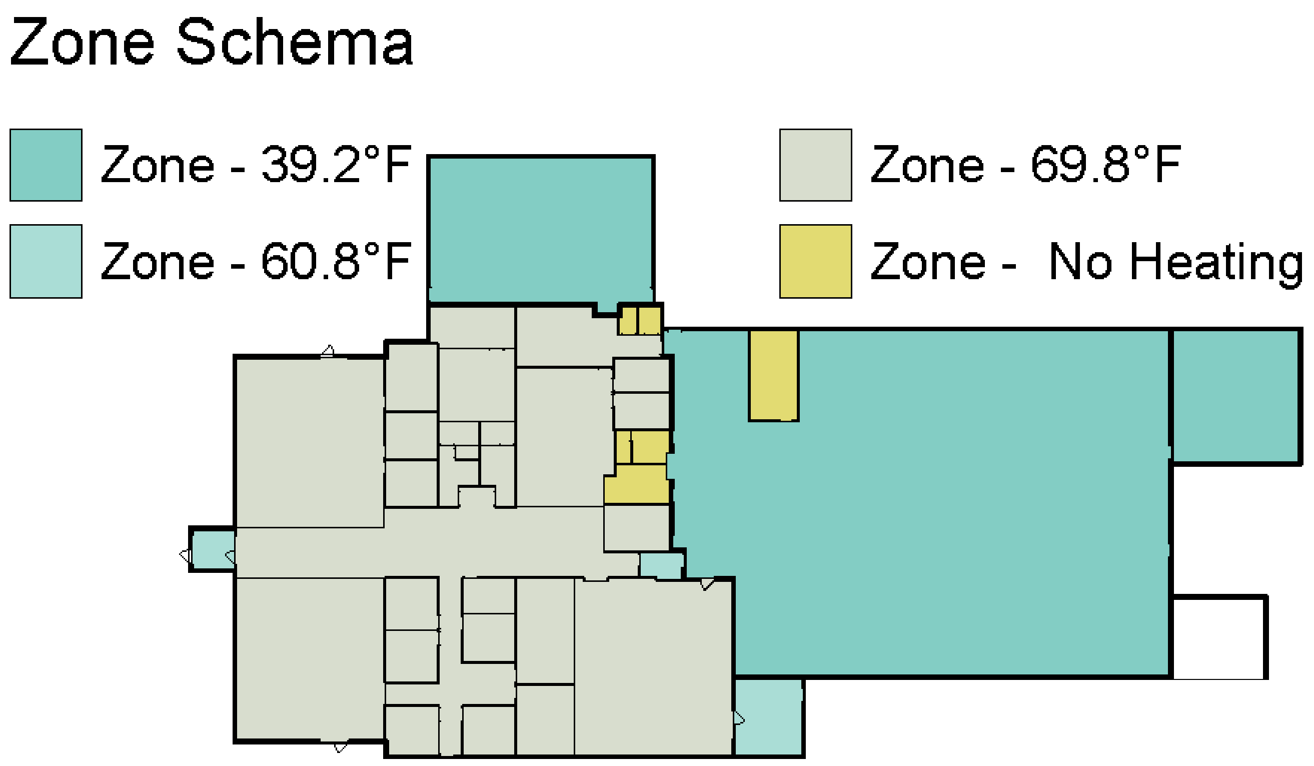


Figure 15 - Zone Schema

Individual thermal comfort controls should be provided for at least 50% of individual occupant spaces. Group thermal comfort controls should be provided for all shared multi-occupant spaces, and for any individual occupant spaces without individual controls. Thermal comfort controls allow occupants, whether in individual spaces or shared multi-occupant spaces, to adjust at least one of the following in their local environment: air temperature, radiant temperature, air speed, and humidity.

5.6.4 Air quality

Each ventilation system that supplies outdoor air to occupied spaces must have particle filters or air-cleaning devices that meet one of the following filtration media requirements: minimum efficiency reporting value (MERV) of 13 or higher, in accordance with ASHRAE Standard 52.2–2007.

They must be also equipped with controls monitoring volume of fresh air supplied to zones, so the Minimum Indoor Air Quality is ensured permanently. In case of not meeting a minimal fresh air volume a voice and light warning signal should be sent to the users.

Additionally, when construction of the building is complete and occupancy period hasn't started yet, a **building flush-out** should be performed by supplying a total air volume of 14,000 cubic feet of outdoor air per square foot of gross floor area, while maintaining an internal temperature of at least 60°F and no higher than 80°F and relative humidity no higher than 60%.

After running a flush-out, special Indoor Air Quality tests should be performed in laboratory, to ensure that levels of harmful chemical substances in indoor air are acceptable.

5.6.5 Motivations

Sick Building Syndrome is a medical condition where people in a building suffer from symptoms of illness or feel unwell for no apparent reason. They may suffer from irritation of the eyes, nose, throat, skin; general health problems; nonspecific hypersensitivity reactions; infectious diseases; and odor and taste sensations. The reason of these problems is poor HVAC systems operation. All these factors can cause low productivity and motivation of employees.

A building that is "sick" will also have a lower Rental Income.

It is economically justified to ensure a good operation of all HVAC systems in a building in order to provide healthy working and living environment for building occupants.

5.7 SYNERGY WITH ARCHITECTURE

Proposed designs shall be well-balanced with a building's architecture. It means that every single part of MEP design should not disturb an architecture concept but rather fulfill it. Space occupied by HVAC devices should be minimized.

These strategies can be realized for example by:

- using unexposed ducts hidden above suspended ceiling or using esthetic fabric ducts in colors adequate to interior design
- using underfloor heating instead of conventional radiators - underfloor piping is invisible for user and doesn't occupy and space in room, so it doesn't collide with interior design
- infrared heating panels with decorative function
- locating AHU units on roof - they can also be covered by dedicated curtain walls, what also lowers the noise
- locating wind turbines in a way they don't have an impact on architectural façade.

All HVAC systems should match the building envelope design properties - e.g. heating system should meet all heat demand and not require adding any extra insulation, or changing the windows type, etc.

5.8 ACOUSTIC CONTROL

The HVAC systems should be selected upon the following criteria: Office Administrative, Living and Meeting Spaces should have maximum sound NC 35 and Meteorological maximum level at NC 30.

6 DESCRIPTION OF SYSTEMS CONSIDERED

The following systems were considered and analyzed:

Baseline

Packaged Rooftop Air Conditioner (PSZ AC)

Fossil Fuel Furnace and DX Cooling

Basic system which covers building heat demand with a central hot-air heating system in a direct-fired technology.
A Constant Air Volume system delivers warm air to all zones throughout the building. The system depends on a furnace, powered by natural gas. Air is humidified by duct gas steam humidifier. Domestic Hot Water is produced by Gas Storage Water Heater.

Advantages:

- simple design
- low first cost

Disadvantages:

- a risk of thermal discomfort due to non-flexible control
- energy inefficient

System 1

Water Source Heat Pump (WSHP)

Main idea of this system is to use heat from the sea water and also recover it from IT servers. Heat from seawater is transferred via propylene glycol to electric heat pumps. There are two heat pump units - one designed for underfloor heating system and another one to cooperate with AHU and produce DHW.
Heat pumps and hydronic pumps used in system are powered with electricity taken both from power grid and produced by 3 on-site wind turbines and PV panels.

Advantages:

- reduced CO_2 emissions
- high share of renewable energy sources
- energy efficient
- low operation costs
- low maintenance costs

Disadvantages:

- high first cost
- risk of system contamination with barnacles and other biological growth in the heat exchangers

System 2

Gas Heat Pump & Boiler (GHP&CB)

System is based on a hybrid heat source - a gas-powered air-to-water heat pump combined with a condensing boiler. Heat source is equipped with advanced control that automatically selects current most energy-efficient operation way. During warm days' heat pump is operated, during coldest - system relies on a boiler. Heat will be delivered to rooms with a low-temperature underfloor heating system.

Advantages:

- energy efficient
- easy, low-cost installation
- flexibility
- long life expectancy

Disadvantages:

- non-renewable energy source
- high operating cost

System 3

Wind Energy Radiant Heating (WERH)

In this system electricity from wind energy covers all energy loads. Wind Energy is emission-free, renewable and cheaper compared to grid electricity. There is no fossil-fuel usage. Infrared Heating Panels provide 100% energy efficient heating. It means that 1 kWh of electricity is transformed into 1 kWh of heat. Far Infrared heating is 100% natural for human body and provides higher thermal comfort than air heating. It reduces carbon emissions when combined with renewable energy. Applied as mirrors or white stylish panels are complementary to interior design.

Advantages:

- reduced CO_2 emissions
- thermal comfort
- synergy with architecture
- reduced pipes
- renewable energy

Disadvantages:

- high first cost
- high replacement cost

6.1 WATER SOURCE HEAT PUMP (WSHP)

Water source heat pump was taken into consideration due to its economic advantages. Heat exchanger receives heat from the sea and then refrigerant fluid is additionally heated by the servers through immersion cooling system (described in greater detail in section no. 7.1). This system is both beneficial for servers and HPs. COP value (fluctuating from 4,5 to 6,5) increases along with a rise of source's temperature.

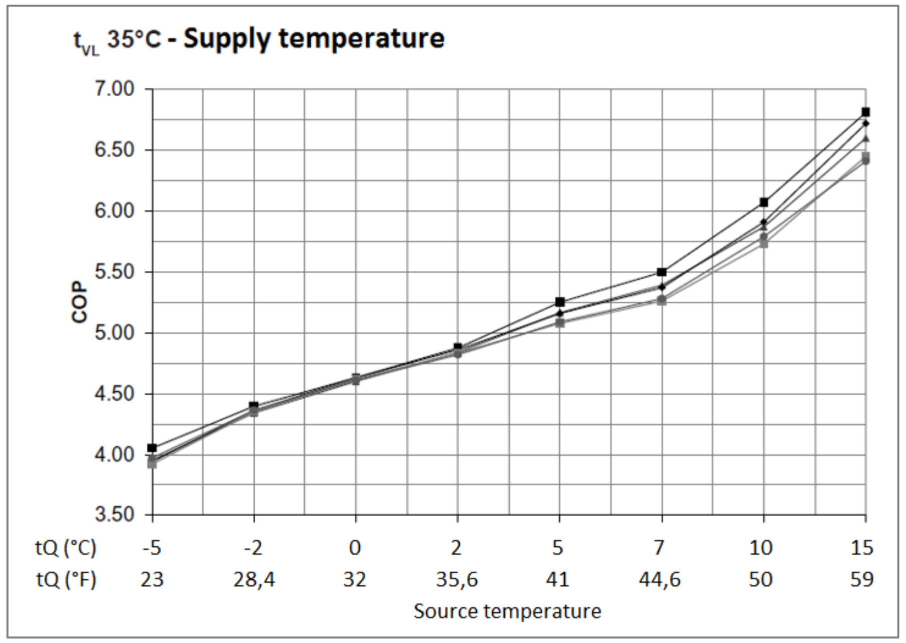


Figure 16 – COP chart for Heat Pumps

This system has two heat pumps, that work on R134a and R410A refrigerants. Heat from the sea is transferred with propylene glycol through HDPE pipes.

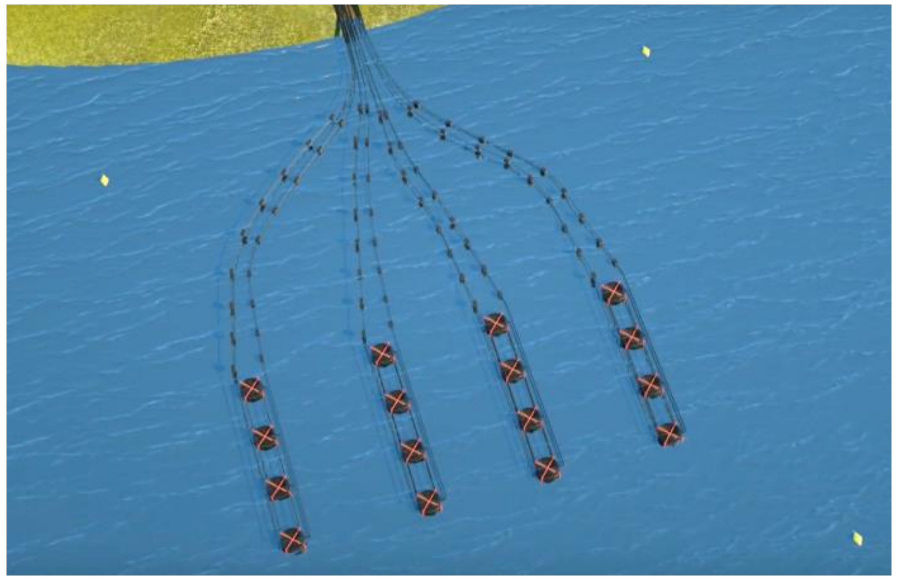


Figure 17 - Sea loop heat exchanger

R-134a in HP1 loop reaches 105°F temperature - it is used for an underfloor heating system.

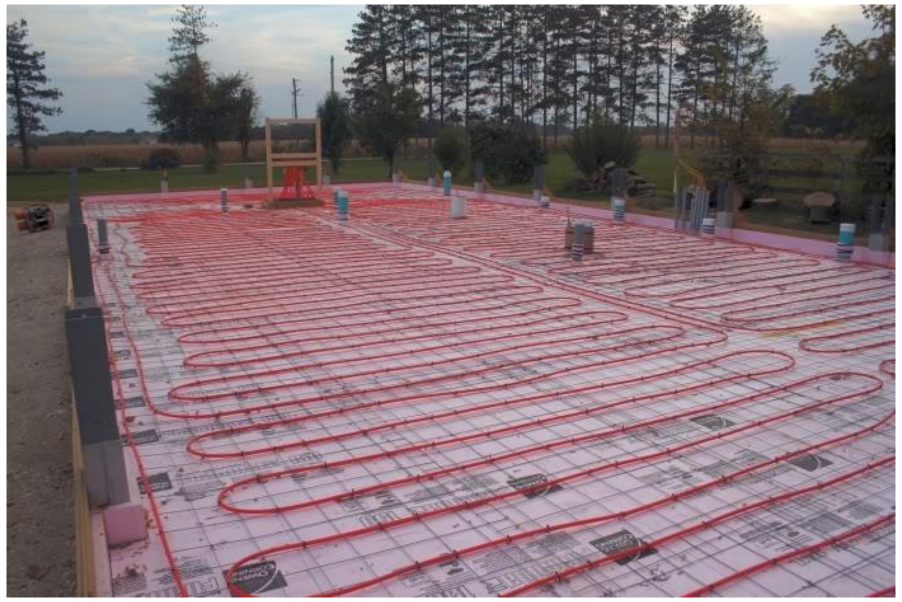


Figure 18 – Underfloor heating PEX piping

HP2 loop has a supply temperature equal 131°F - this one is used for producing DHW and heating air in an AHU unit.

1300 ft^2 of PV panels sponsored by a local donor cover 5% of total energy needs. In this system, PV panels number was increased with another 3300 ft^2. Also, another three wind turbines, each with 5kW of power, were added. These renewable sources covered 59,7% of total energy needs.

Electricity demand for the building is unremitting - 24/7. This system relies on electricity, which is provided by wind turbines and PV panels.

The WUT team chose 300 kWh and peak 50kW DC energy storage devices with inverter for both DC – AC and AC - DC conversion, emergency backup and load shifting for using stored energy, when "On Peak" prices occur.

Renewable sources save 59,7% of total energy needs. Load shifting saves 19,3% of energy costs. Heat synergy provided by cooperation with Data Center immersion cooling system, provides higher efficiency of heat pumps. DC energy storage device with ability to work as UPS, reduces first costs of server room

Another advantage of this system is a full independency from fossil fuels. It also reduces CO_2 emissions.

6.2 GAS HEAT PUMP & CONDENSING BOILER (GHP&CB)

Gas powered system has been considered due to its long-life expectancy, which is an important factor - servicing and replacement of appliances is difficult on an isolated island. Even though this idea relies mostly on non-renewable energy, it involves the most efficient way of using it.

Heat source used in this system has a hybrid nature. Depending on outdoor conditions it automatically chooses the most efficient way of operating. During warm days (outside temperature higher than 39°F) a heat pump works efficiently and its COP factor is high, so it works in a "heat pump only mode". In Diego Ramirez conditions, it happens on 65% of year. When outside temperature falls (between 19-39°F), it automatically switches to a hybrid mode - a gas condensing boiler turns on and cooperates with a heat pump - it performs a supportive role.

Device has also a third operation option -although in given conditions it has a minor meaning. If temperature falls below 19°F it switches to a "boiler only mode" and this happens only for 11 hours a year what makes it almost unnoticeable. However, this system is flexible and could work efficiently even in lower temperatures, which is an advantage.

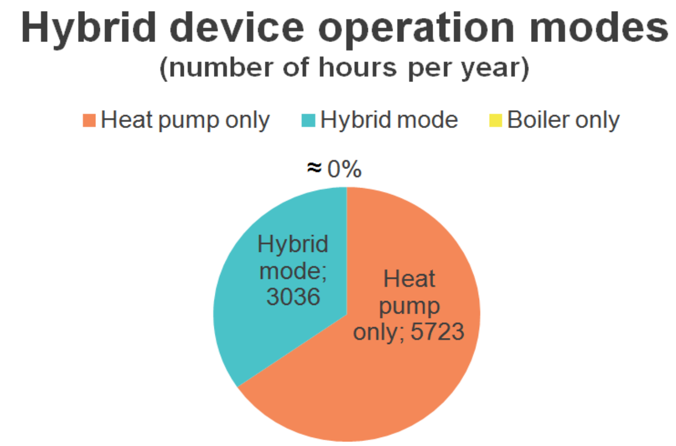


Figure 19 – Hybrid device operation modes

Gas boiler used in a hybrid device is a condensing one. It means that it recovers latent heat from exhaust fumes, rather than letting it directly to atmosphere, like in a conventional boiler. It allows this device to achieve efficiency as high as 97%.

Thanks to combining two different appliances (a heat pump and a boiler) a total life expectancy of a hybrid device can get even doubled.

Just like in a previous solution (WSHP), heat will be delivered to rooms with an underfloor heating system. This goes well with using low temperature heating medium, which is an efficient way of delivering heat.

The Heat Pump component of system contains R-410a refrigerant. It's widely used thanks to not being an ozone-depleting substance. However, it has a high Global Warming Potential. A disadvantage of this system is that it mostly relies on an non-renewable energy source. The only renewable part of a system are PV panels described above. Power generated by them would be used to cover electricity needs of a building, rather than heating. GHP&CB system also involves using a refrigerant which is not fully environment neutral.

On the contrary it works in a very efficient way and it has very long life expectancy, which is important on an isolated island - there isn't any problem with maintenance and replacement. Natural gas is also a relatively low-cost medium, so using it doesn't increase LCC a lot. This solution is also flexible - it could handle even more harsh weather conditions.

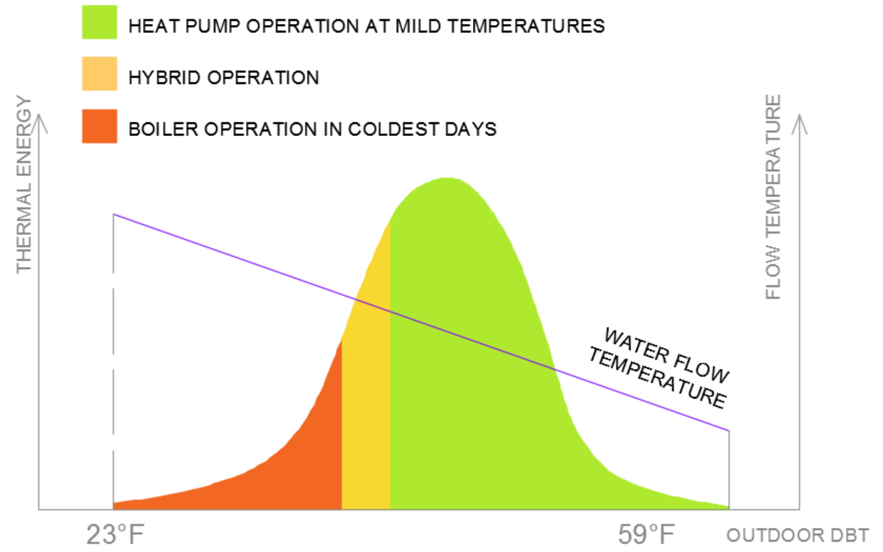


Figure 21 – Hybrid device operation parameters

6.3 WIND ENERGY AND RADIANT HEATING (WERH)

Weather Data analysis confirmed that wind energy shall be effective in that design. After calculating prices per 1 kWh of electricity by grid, solar energy and wind energy, this alternative appears to have lowest life cycle cost

The biggest disadvantage of applying wind energy is high cost of wind turbines and noise. Turbines cannot be placed near the building; a minimum distance is required.

Nevertheless, wind energy is 100% renewable, emission free and sustainable.

Wind turbines are designed to cover minimum heating and electricity loads. It means that during peak usage wind turbines do not cover 100% needs. But besides that, it is much more effective than electricity from grid.

There is no fossil fuel usage in this system so heating loads can be covered by an electric-based solution. It was assumed that the best way to heat the building is to apply radiant heating.

Figure 20 - Wind turbines

Radiant heating is implemented by infrared heating panels. These are flat panels hosted to walls, white or mirrored (so it basically looks like an ordinary mirror).

Radiant heating provides higher thermal comfort than air heating due to fact that long wave infrared heats solids. The heating effect is similar to warmth from the sun. Air is not heated so there will be less dust and pollutants. Infrared heating panels in bathrooms make walls dry so the risk of damp or mould is very low.

Figure 22 – infrared radiant heater

Following Figure presents wind generated electricity compared to total energy needs.

It seems that wind generated electricity covers a big part of energy needs but in fact, for 2650 hours a year, there is still a need to supply this system by grid. Nevertheless, price per BTU of electricity in that combined system is 75% lower than price of electricity from grid. The excess wind energy can be returned to the grid. Energy is never wasted, there is a buyback rate at which electricity can be bought at lower price 0,077$ per kWh

Domestic Hot Water may be heated by Electric Water Heater supplied by Wind Energy.

Main advantage of this system is that building is nearly energy-independent and the energy is renewable. Although wind turbines are noisy and have an impact on exterior site, they will be located in required distance from building. The noise coming from wind turbines should not be disturbing. These wind turbines should be replaced after 20 years.

AHU will be also supplied by wind generated electricity.

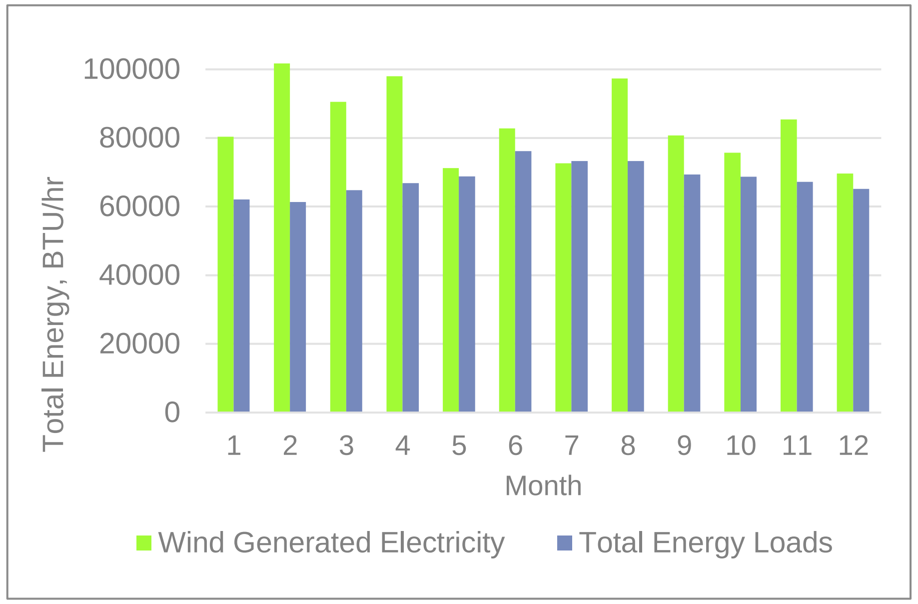


Figure 23 – Wind Generated Electricity compared to Total Energy Loads

6.4 VENTILATION SYSTEMS

Since heating was considered to be a primary system for a building, ventilation and cooling systems are the same in all 3 proposed designs. They are described in this section.

6.4.1 Mechanical Ventilation

Building will be supplied with fresh outdoor air by **two centralized systems**, operated with two AHU's.

The first AHU prepares supply air for dwelling units and office area. It contains a plate heat exchanger for heat recovery, air heating-coil, air steam humidifier, fabric air filters and RCI filtration device.

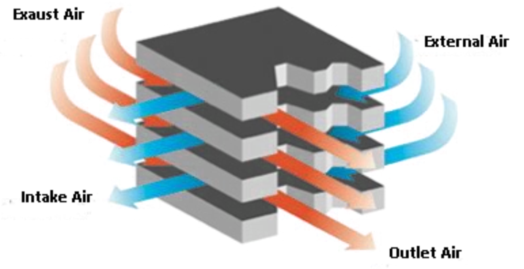


Figure 24 – Fixed-plate heat exchanger (crossflow)

The second AHU is responsible for Car Service Area in building - Car Service Hall, Car Wash and Garage. For non-residential spaces, where cars engines are operated, a direct exhaust system is provided. The idea of system serving garage is described in greater detailed in Section 7.2.

Due to highly varying value of internal gains (from people, lighting and equipment), Conference Room and Learning Center have a separate **Demand Control Ventilation** System. A CO2 sensor is located inside of the rooms and it controls the air supply. When CO2 concentration exceeds 700ppm value a fan starts working and it supplies fresh air to remove contamination.

Air distribution may be done by **Fabric Ducts**. These ducts are cheaper, lighter and easier to install than traditional steel ducts. Air is distributed by orifices installed in fabric. Due to fact that some spaces are supplied by Variable Air Volume, Fabric Tensioning System is applied. It means that ducts have the same appearance with any air pressure change. Air supplying spaces by Fabric Ducts can be distributed up to 20 fps.

Figure 26 - Fabric duct installation example

Fabric Ducts provide better thermal comfort because of increased level of air mixing and better air distribution. Fabric Ducts act partially as air filters. They are more hygienic because cleaning them can be done by common laundry. They also have an esthetic look, so they match interior design of a building.

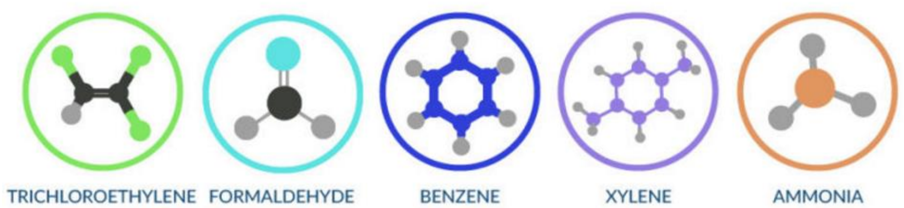
For air filtration and bacteria removal **Radiant Catalytic Ionization Technology** is used. A device is installed in an AHU.

Figure 28 - Volatile organic compounds (VOCs)

Figure 25 – RCI devices

The most important element of a device is a matrix with hydrophilic properties. When the device is turned on, UV radiation hits the matrix's honeycomb structure, catalyzing chemical reactions. As a result, superoxide and hydroxide ions are created. They eliminate the pollutants not only being close to the matrix, but when air containing ions leaves the device, it acts as a "plasma purifier" - destroying microorganisms, oxidize gaseous organic compounds and remove the unwanted odors inside the rooms.

Additional air filtering is present inside of rooms. A research on clean air made by NASA has found that certain plants can assist in removing harmful VOCs from the air, like benzene, ammonia, or formaldehyde. Their negative impact on health of room occupants is proven.



That's why the team recommends using certain types of pot plants that can help improving IAQ.

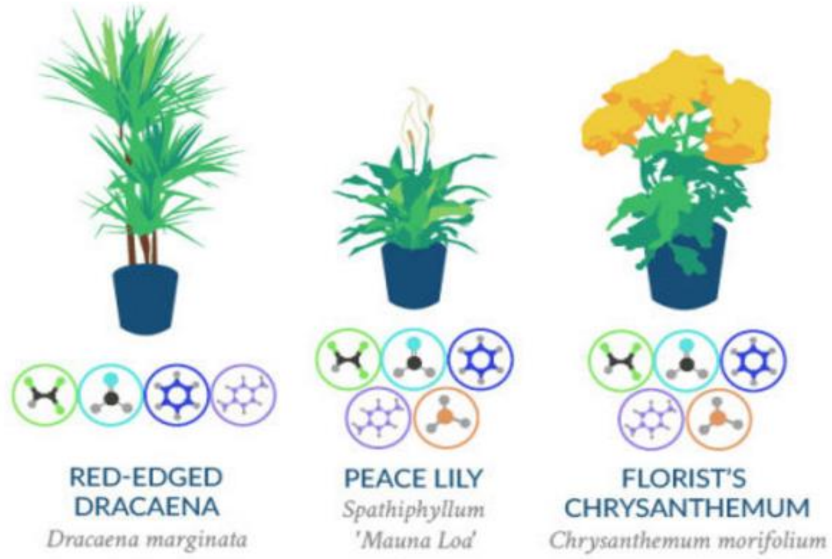


Figure 27 - Recommended air-filtering plants by NASA

A detailed Ventilation Schema is presented in Appendix D.

6.4.2 Cooling

The building has a low cooling demand. Besides Data Center, there are only a few rooms with a need to be cooled, (Kitchen and Parts Office). Having said that, cooling demand is too little to invest in any powerful cooling system.

Outdoor DBT is lower than indoor design temperature all year long, so it is a brilliant occasion to use free-cooling technology.

ASHRAE Standard 90.1 recommends using an economizer for cooling needs in a considered climate zone. However, because there are few rooms with a cooling demand, the team implemented a micro free-cooling DOAS serving the rooms a with a need to be cooled.

Besides general supply system, they have a second, parallel pair of ducts that supply cold, unheated external air to meet a cooling load. An advantage of this solution is avoiding the use of refrigerants, which can be harmful to environment. It is also very simple and low-cost solution.

Cold air is supplied thanks to modulating speed fan. Fan is connected to a thermostat controlled by occupants.

6.4.3 Acoustic Control

To achieve required sound levels from Section 5.8 materials should be with accordance to standard 189.1-2014 Section 8.3.3.3. Outdoor-Indoor Transmission Class (OITC) values for assemblies and components shall be determined in accordance with ASTM E1332 and Sound Transmission Class (STC) values for assemblies and components shall be determined in accordance with ASTM E90 and ASTME413. For measurements, use a sound lever meter that conforms to ANSI S1.4 for sound measurements instrumentation. Achieve maximum background noise levels from HVAC systems per 2011 ASHRAE Handbook, HVAC Applications Chapter 48, Table 1; AHRI Standard 885-2008, Table 15.

7 SPECIAL ROOMS

7.1 DATA CENTER

Building will contain a Data Center room. Room cooling demand is estimated to be 4.3 tons. Servers need to work at optimal temperatures and humidity range.

Team decided to apply a two-phase immersion cooling instead of widely used traditional air-conditioning systems. This new solution is more eco-friendly and energy-efficient.

Owner's Project Requirements of Data Center room were considered to be inefficient, ASHRAE recommends class A1 data center range in temperatures from 59ºF to 89,6ºF and 20-80% RH. These conditions allow to use air side economizer. Hot-aisle and cold-aisle arrangement can help distribute air properly. In-row cooling can precisely cool the equipment.

Immersion cooling works with HFE fluids. They do not conduct electricity and have low Global Warming Potential. Racks are directly cooled by fluid which evaporates at 142ºF. The bath is semi-open as it is at atmospheric pressure. Condenser heats water which can be used for example as a domestic hot water.

There is no need to maintain specific indoor parameters in room because the whole cooling process is in a bath. Fluid is nontoxic.

This system can provide PUE lower than 1.05 and reduces electricity usage.

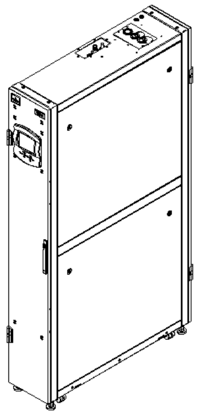


Figure 29 - In-Row Cooling Unit

7.2 GARAGE ROOMS

7.2.1 Standards

Most codes require a minimum ventilation rate to ensure that the CO concentration does not exceed safe limits. ANSI/ASHRAE Standard 62.1 recommends a ventilation rate of 1.5 cfm/ft^2 for automotive service stations. The high ventilation rate indicates that the contaminants are not related to the occupants, but are produced by the variety of tasks and materials used in the facility. Outdoor ventilation is introduced into the space and an amount approximately equal quantity is exhausted through a dedicated exhaust system.

Predicted CO Emission in Parking Garage was assumed to be 0.447 lb/h according to EPA MOBILE3. Average Entrance and Exit Times for Vehicles was assumed to be 80 s. ASHRAE-62.1 recommends Regulatory Level of carbon monoxide in accordance with NAAQS/EPA 9 ppm should not to be exceeded more than once per year.

7.2.2 Concept Overview

A Baseline system contains constant-volume ventilation based on recommended ventilation rate. Proposed system shall be operated by on/off control with fans stopped and started based on input from CO sensors.

Following assumptions were made:

- → Number of cars N = 2
- → Average CO emission rate E for a typical car, lb/h
- → Average length of operation and travel time θ for a typical car, s
- → Acceptable CO concentration CO_{max} in the garage, ppm
- → total floor area of parking facility A_f, ft^2

Peak CO generation rate was determined by following formula:

$$G = \frac{NE}{A_f}, \quad \frac{lb}{h \cdot ft^2}$$

Peak CO generation rate was normalized using the reference value $G_0 = 5{,}46 \cdot 10^{-3}$ lb/h · ft^2:

$$f = 100\frac{G}{G_0}$$

Minimum ventilation rate Q per unit floor area was determined by following formula (where C = 2.370·10^{-4} cfm/ft^2·s for CO_{max}=15 ppm):

$$Q = Cf\theta, \quad \frac{cfm}{ft^2}$$

Minimum ventilations rates for Vehicle Parking and Service Hall are 0,0017 cfm/ft^2 and 0,00035 cfm/ft^2.

7.2.3 Engine Exhaust

The Owner wishes to have a vehicle exhaust system installed for this purpose. Vehicles run twice a week per 45 minutes. Engines are a standard V-8 Diesel engine.

Tailpipe emissions include Nitrogen oxides (NO_x), Carbon monoxide (CO), Hydrocarbons (HCs) and Volatile organic compounds (VOCs). Diesel engines emit mainly NOx and HC.

According to Donaldson Exhaust Product Guide Exhaust Flow for a V8-300-M Diesel engine shall be 1528 CFM at 950ºF. Testing systems runs periodically and shortly so team decided to extract exhaust gases, without any heat recovery. Extracting will be performed by dedicated flex pipes. This solution allowsto using only CO peak sensors.

Figure 30 - Exhaust extraction nozzle with internal grip

8 PROJECT SUSTAINABILITY ANALYSIS

8.1 ENERGY USAGE

8.1.1 Primary & Renewable Energy

All 3 systems have a share of renewable energy sources (these are PV panels, included in all solutions) and two design options are almost fully independent from non-renewable energy sources - wind and solar power are used to produce both electricity and heat.

Using wind and solar energy is economically justified by the small cost of 1 kWh of energy, comparing to energy bought from grid (during on- and off-peak time). Results are presented on a figure 15 - wind and solar generated electricity have a cost low enough for the investment to payback during 50 years.

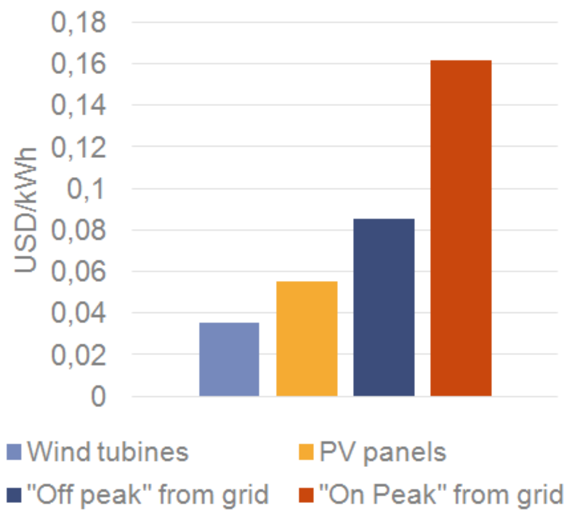


Figure 31 - Price per 1 kWh of Electricity depending on system

Only system no. 2 (GHP&CB) bases on fossil fuels, however using highly efficient hybrid device with a long service life makes this solution economically justified.

8.1.1.1 Wind energy

Analyzing annual wind speed values brings to conclusion that generating electric energy from wind is possible during 84% of whole year. The average cost of energy generated by turbines is around 5,5 ¢/kWh.

Horizontal axis, three-bladed rotor wind turbines were implemented in two of designed systems.

8.1.1.2 Solar energy

A local donor has offered to provide funding for the installation of a photovoltaic array, that supports 5% of the total building energy needs (170,6 MWh), which is 8,5MWh - this system is included in all 3 design options.

The team ussumed the type of panels: monocrystalline, silicon panels with an average 13% efficiency. Using hourly analysis in IES VE software the team calculated that 1300ft² of such PV panels is needed. PV panels are faced in North direction and tilted 30 degree from horizontal surface. They are located on a roof surface.

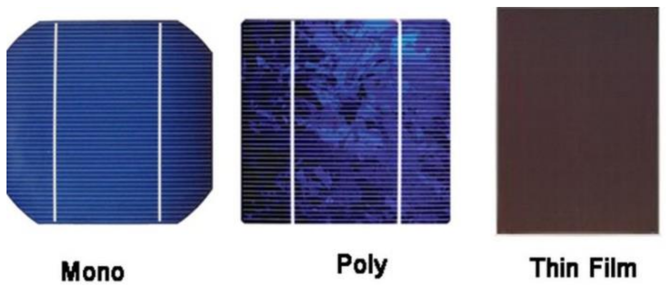


Figure 32 - Typical solar cells

Total cost of PV instalation with inverters is estimated around 15 000$/25years.

With this application, 28 000$ is saved on electricity, during a considered building life cycle time (50 years).

Additionally, in a first design option (WSHP) 3300 ft² of extra panels are included.

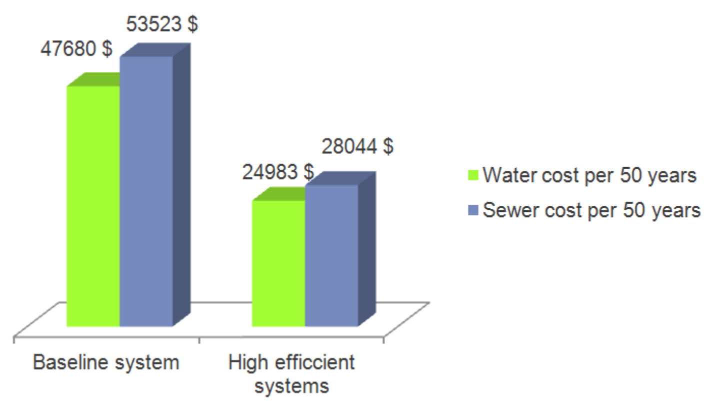


Figure 35 – Water and sewer costs in both systems (during 50 years)

8.1.1.3 Accumulation - load shifting

Option 1 (WSHP) has another advantage - using Energy Storage Device allows to lower operating costs of system. Electricity from grid is used only while "off-peak" prices occur. Wind turbine generated electric power is stored and used it when higher “On Peak” prices appear.

8.1.2 Energy Conservation Measures

A Building Management System (BMS) should be implemented in order to monitor and analyse building energy usage. Servers that are installed in a building can be used for this purpose.

According to LEED v4 for Building Design and Construction whole-building and any individual energy end (AHU, HP, DHW boiler, lighting, server) uses that represent 10% or more of the total annual consumption of the building should have advanced energy metering installed.

Such a detailed analysis creates a possibility to inform building users about a current energy usage, or even organize a kind of competition. Its aim is to reduce a usage value as much as possible. All data would be presented on TV screens with graphs and information about used equipment and its current state, so the people would feel involved in game.

For example, an important part of electricity demand is consumed for lighting - it is caused by a little amount of daily light, due to small windows area and low altitude of the sun. Building occupants have a big impact on this value - they can simply turn the light off, when not really needed. Participating in a game will make occupants feel more motivated to pay attention to wasting energy.

Data about building performance can be shared online as a kind of building case study. Other people can learn about building energy usage. Such approach is gratified by extra LEED points in an Innovation credit.

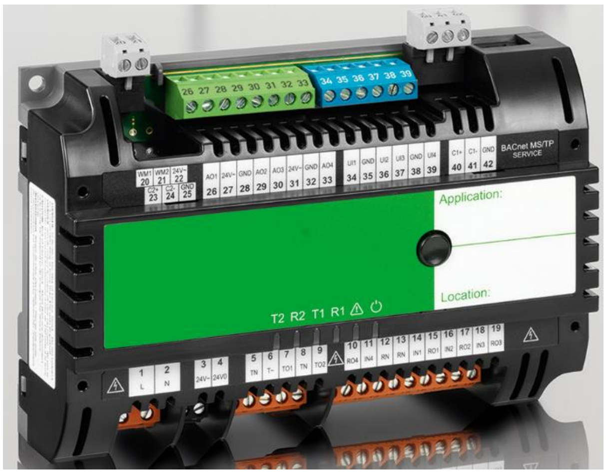


Figure 33 – Building Management System (BMS) devices

8.2 WATER USAGE DISCUSSION

Water usage has been lowered by inserting ultralow flow plumbing fixtures. When water usage exceeds 2,5 gallons, a flashing red LED lamp gives warning to a user. Plumbing fixtures have mist nozzles, which reduce water flow even by 90%, comparing to conventional solutions. Team also decided to reuse greywater for non-potable uses, like flushing toilets. By using more efficient solutions we managed to reduce water usage by 49% and save nearly 1000$ on average per year. The actual water consumption would be measured by permanent water meters installed on plumbing fixtures, DHW installations and reclaimed water installations.

Figure 34 - Faucet aerator with a mist nozzle

An extra consequence of reducing water usage, is decreasing overall energy consumption - less energy is used to prepare DHW.

8.3 REFRIGERANTS DISCUSSION

The following substances are used in proposed design options:

Used Refrigerants			
Name	ODP	GWP	Application
HFE 7100	0	320	Immersion Cooling
R134a	0	1300	WSHP
R410A	0	2000	WSHP and GHP

Table 5 - Refrigerants used in proposed designs

Figure 37 – Refrigerant 134a

Figure 36 – Refriferant 410A

All 3 proposed systems include usage of refrigerant substances. In systems with Heat Pumps they act as a heating medium. Additionally, in all designs Data Center servers are cooled with the HFE7100 substance. The impact of refrigerants has been considered in system rating process.

8.4 CARBON FOOTPRINT

Carbon footprint is reduced by:

- → recycling and reusing refrigerants with high GWP
- → reducing overall energy consumption by reducing water usage, installing energy-efficient LED lighting, using efficient Data Center cooling system (Immersion Cooling reduces PUE even to 1.02)
- → using renewable energy sources in order to lower energy consumption from the grid and its GWP potential
- → additional air filtration by plants

8.5 LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN (LEED)

LEED is an internationally recognized certification system that measures how well a building or community performs across all the metrics that matter most: energy savings, water efficiency, CO2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts.

All 3 considered systems have been judged in accordance with the newest version LEED v4 rating system.

Only credits applicable to HVAC design, that matched the scope of study of System Selection competition category, were taken into consideration. They belong to 4 categories: Water efficiency, Energy and Atmosphere, IEQ and Innovation.

According to LEED grading system achieving 40 points amount is enough to call a building "LEED Certified".

Applicable credits	Possible points	WSHP	GHP	WERH
Water efficiency				
Indoor water use reduction	6	5	5	5
Water metering	1	1	1	1
Energy and Atmosphere				
Enhanced Commissioning	6	6	6	6
Optimize energy Performance	18	11	9	14
Advanced Energy Metering	1	1	1	1
Renewable Energy Production	3	3	2	3
Enhanced Refrigerant Management	1	0	0	0
Indoor Environmental Quality				
Enhanced Indoor Air Quality Strategies	2	2	2	2
Indoor air quality assesment	2	2	2	2
Thermal Comfort	1	1	1	1
Acoustic Performance	1	1	1	1
Innovation				
Innovation	5	1	1	1
	47	**33**	**31**	**37**

Table 6 - LEED v4 for BD+C: New Construction and Major Renovation Project Checklist

9 LCCA - LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis calculations were based on the following formulas:

- F_t - Future cost:
  $$F_t = F \times (1+i)^t$$
- PV - Present Value:
  $$PV = \frac{F_t}{(1+d)^t}$$

Where:

t – life of the building, t=50 years

i – inflation rate, i=3%

d – rate of return d=4%

Each of the cost values were based on industry statistics, ASHRAE Handbooks and common technical data. Maintenance and replacement costs were taken from industry statistics of individual companies. Life cycle values were included in technical data of designed equipment. Inflation rates for utilities are in Energy and utility rates provided by the owner Section 2.5. are also used to calculate annual utility costs. Life Cycle Cost Analysis was calculated in 50-year period for all chosen system and compared to the baseline system.

The Initial cost of the **Water Source Heat Pump** with seawater loop is 472 thousand dollars including three wind turbines, PV array with total area 3300 ft² wide, underfloor heating, air handling unit, plumbing for DCW, DHW, two heat pumps with heat buffer, bottom heat source – sea loop, bms system connected to server room, 300kWh energy storage device and immersion cooling for Server Room.

The Initial cost of the **Gas Heat Pump with Condensing Boiler** is 165 thousand dollars including PV array with total area 1300 ft² from local donor, floor heating, air handling unit, plumbing for DCW, DHW, heat buffer, and immersion cooling for Server Room.

The Initial cost of the **Wind Energy and Radiant Heating** System is 356 thousand dollars including five wind turbines, floor heating, air handling unit, plumbing for DCW, DHW and immersion cooling for Server Room cooling.

The annual replacement costs were developed using life cycle data for each individual component.

For example in WSHP System wind turbines are used for renewable energy generation. Each individual wind turbine has a life cycle of 25 years. Innitialy, its materials such as foundation, inverters, cables controllers and wind turbine itself cost 63246 $ and labor work costs 28461 $. Labor work include renting crane services and concrete mixer services for faster foundation formation and also working hours for employees. After 25 years the whole process is reapeted excluding concrete foundation formation.

Replacement cost of WERH system has the highest replacement cost because of more efficient wind tubines which has lower life cycle. GHP&CB has the lowest first cost but its operating cost is the highest compared to other systems. It is cause by the largest share of electricity in total utility consumption. Systems that are more energy independent have more renewable sources and more energy management systems. For example energy storage device or energy controller.

Total Present Value Cost of System is the combination of first cost, replacement cost, maintenance cost and operating cost. Methedology of calculations was taken from CEN - EN 15459 - Energy Performance of Buildings - Economic Evaluation Procedure for Energy Systems in Buildings.

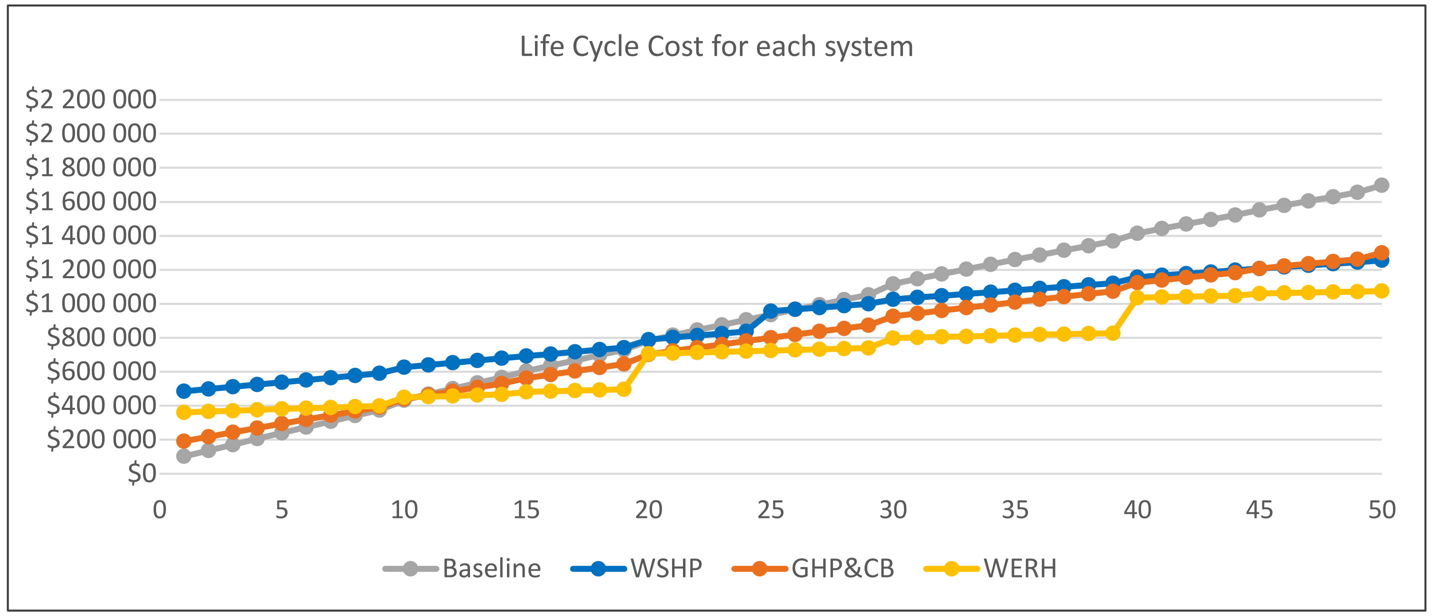


Figure 38 - Total Value cost per for year chart

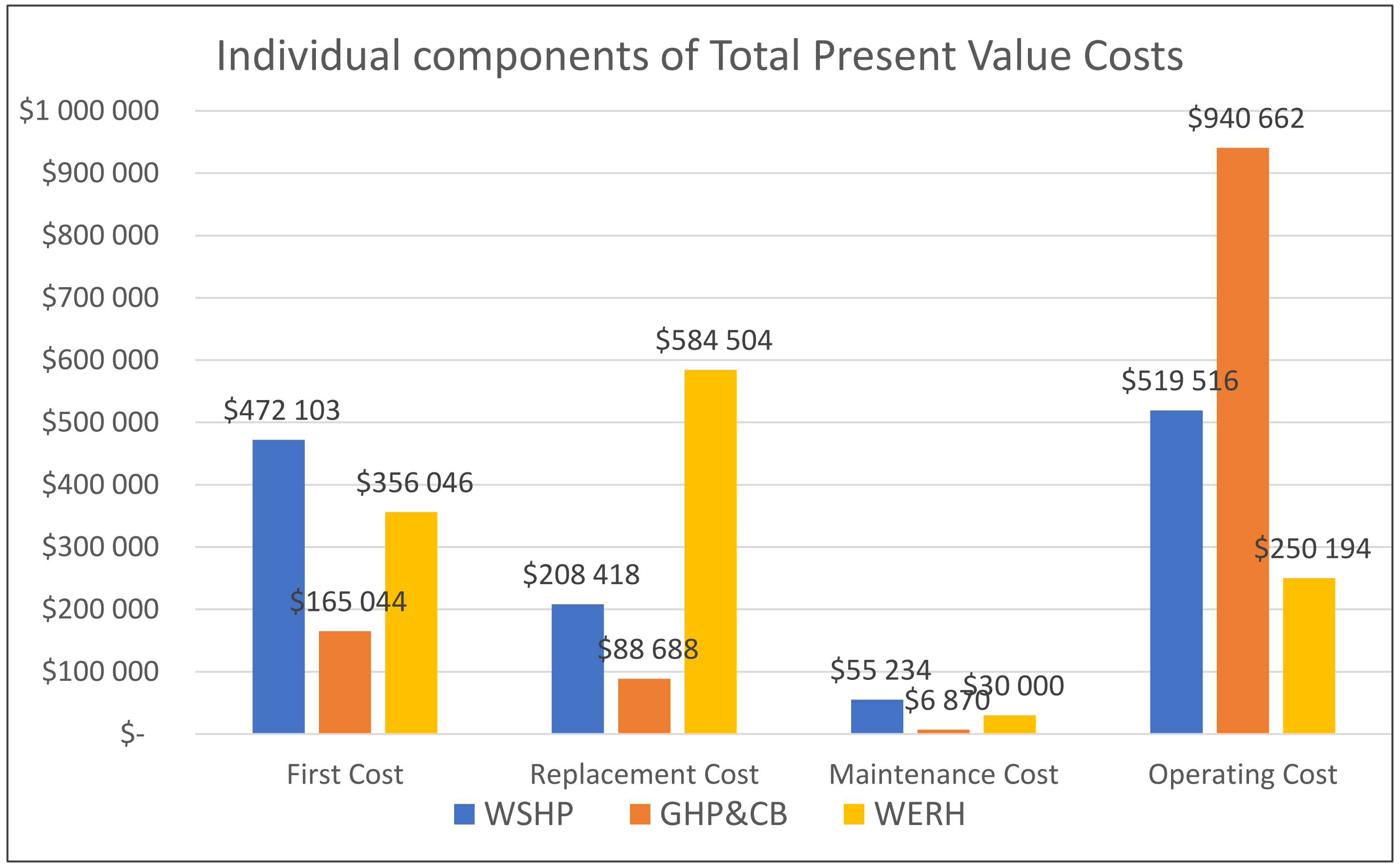


Figure 39 - Individual components of Total Present Value Costs in 50-year analysis

9.1 UTILITIES COSTS

Table 7 - Utilities costs per year

Utilities Cost on each Sysytem per year				Baseline		WSHP		GHP&CB		WERH	
	Annual Increase	Rate	Units	Annual Consumption	Cost	Annual Consumption	Cost	Annual Consumption	Cost	Annual Consumption	Cost
On-Peak Electricity (kWh)	3,5%	0,1614	$/kWh	109672	$17 701	40759	$6 579	104189	$ 16 816	13236	$2 136
Off-Peak Electricity (kWh)	3,5%	0,085	$/kWh	60972	$5 183	13380	$1 137	57924	$ 4 924	5450	$463
Natural gas (Mcf)	3,0%	7,91	$/Mcf	645	$5 102	0	$0	317	$ 2 507	0	$0
City water (cft)	2,5%	0,02	$/cft	99026	$1 981	87044	$1 741	87044	$ 1 741	87044	$1 741
City sewer (gal)	2,5%	0,003	$/gal	185558	$557	95893	$288	95893	$ 288	95893	$288
	Total Utility Cost per year			$30 522,92		$9 744,36		$26 275,62		$4 628,10	

9.2 WSHP FIRST COSTS

Table 8 - WSHP first costs

Water Source Heat Pump			
Item	Material cost	Labor Cost	Total cost
3 Wind Turbines with foundations, controller and inverters	$63 246	$28 461	$91 707
PV panels with controller and inverters	$60 030	$17 000	$77 030
Floor heatng (cyculation pumps, water distributors, 5300yd of pipes and accesories)	$9 418	$3 296	$12 714
Air Handling Unit with ductwork, fans, humidifier and heat exchanger	$38 892	$13 612	$52 504
Hydronic piping, plumbing and receivers eg. Taps,showers	$7 040	$5 400	$12 440
Heat pump 1	$14 000	$3 000	$17 000
Heat pump 2	$8 500	$2 500	$11 000
2*Buffer 200L	$404	$250	$654
Bottom heat source - water pipes in the sea	$46 844	$16 395	$63 240
BMS (sensors, net controller, display boards)	$12 000	$27 600	$39 600
300kWh Energy storage device	$39 000	$5 000	$44 000
Data center Immersion cooling	$23 830	$7 149	$30 979
Total	$342 440	$129 664	**$472 103**

9.3 GHP&CB FIRST COSTS

Table 9 - GHP&CB first costs

Wind Energy and Radiant Heating			
Item	Material cost	Labor Cost	Total cost
5 Wind Turbines with foundations and inverters	$160 000	$72 000	$232 000
Infrared Heaters	$21 470	$9 662	$31 132
Air Handling Unit with ductwork, fans, humidifier and heat exchanger	$7 330	$2 566	$9 896
Hydronic piping, plumbing and receivers eg. Taps,showers	$7 040	$5 400	$12 440
Data center Immersion cooling	$23 830	$7 149	$30 979
BMS (advanced metering, temp. And humid. sensors, net controller, display boards)	$12 000	$27 600	$39 600
Total	$231 670	$124 376	**$356 046**

9.4 WERH FIRST COSTS

Table 10 - WERH first costs

Gas Heat Pump & Condensing Boiler			
Item	Material cost	Labor Cost	Total cost
Gas Heat Pump	$11 537	$4 615	$16 152
Buffer 200L	$404	$250	$654
Air Handling Unit with ductwork, fans, humidifier and heat exchanger	$38 892	$13 612	$52 504
Floor heatng (cyculation pumps, water distributors, 5300yd of pipes and accesories)	$9 418	$3 296	$12 714
Hydronic piping, plumbing and receivers eg. Taps,showers	$7 040	$5 400	$12 440
Data center Immersion cooling	$23 830	$7 149	$30 979
BMS (sensors, net controller, display boards)	$12 000	$27 600	$39 600
Total	$103 121	$61 922	**$165 044**

Replacement and Maintenance Costs

	Replacement cost	Economic life
Equipment Item	[$]	[years]
Air filters	80	0,5
Immersion cooling	23830	10
AHU	20000	25
Boiler	400	25
GHP	16150	20
WSHP 1	17000	25
WSHP 2	11000	10
Infrared heaters	31132	20
Exhaust fans	4500	20
Wind turbines	51800/140000	25
PV panels	77030	20
Energy storage	49000	25
Circulation pumps	4500	25

*All replacements costs include labour, and they are not expressed in the present value.

Maintenance costs include cleaning, oiling, testing and repairing equipment which occupants can't do by themselves. Maintenance costs are low due to full BMS system which lowers costs to minimum.

Table 11 - Replacement & Maintenance Costs

Life Cycle Cost				
Year	Baseline	WSHP	GHP&CB	WERH
0	$65 934	$472 103	$165 044	$356 046
1	$101 733	$484 985	$191 579	$360 934
2	$136 638	$497 752	$217 735	$365 755
3	$171 290	$511 456	$243 517	$370 511
4	$205 692	$525 084	$268 932	$375 201
5	$240 713	$538 585	$294 883	$380 728
6	$274 624	$551 960	$319 577	$385 292
7	$308 293	$565 211	$343 919	$389 793
8	$341 722	$578 340	$367 913	$394 234
9	$374 914	$591 348	$391 565	$398 614
10	$433 114	$626 023	$439 611	$449 136
11	$468 686	$639 447	$462 593	$453 398
12	$501 180	$652 745	$485 247	$457 602
13	$533 446	$665 918	$507 578	$461 750
14	$565 487	$678 968	$529 591	$465 842
15	$603 520	$691 895	$562 191	$480 778
16	$635 116	$704 702	$583 581	$484 760
17	$666 492	$717 390	$604 666	$488 688
18	$697 650	$729 960	$625 451	$492 563
19	$728 594	$742 413	$645 940	$496 386
20	$782 242	$788 769	$702 405	$706 358
21	$815 346	$800 994	$722 315	$710 080
22	$845 656	$813 107	$741 941	$713 751
23	$875 758	$825 109	$761 288	$717 373
24	$905 654	$837 001	$780 359	$720 946
25	$936 061	$956 796	$800 560	$725 372
26	$965 552	$967 156	$819 092	$728 850
27	$994 843	$977 428	$837 362	$732 282
28	$1 023 935	$988 382	$855 371	$735 669
29	$1 052 832	$999 240	$873 125	$739 010
30	$1 115 912	$1 026 296	$925 357	$798 507
31	$1 146 647	$1 036 965	$942 609	$801 760
32	$1 174 965	$1 047 541	$959 617	$804 970
33	$1 203 092	$1 058 025	$976 383	$808 138
34	$1 231 032	$1 068 419	$992 911	$811 263
35	$1 259 433	$1 078 722	$1 010 104	$815 247
36	$1 287 002	$1 089 393	$1 026 166	$818 290
37	$1 314 387	$1 099 969	$1 042 000	$821 294
38	$1 341 591	$1 110 452	$1 057 609	$824 257
39	$1 368 614	$1 120 842	$1 072 997	$827 182
40	$1 414 351	$1 156 581	$1 124 435	$1 036 269
41	$1 443 150	$1 166 790	$1 139 390	$1 039 117
42	$1 469 642	$1 176 910	$1 154 133	$1 041 928
43	$1 495 961	$1 186 942	$1 168 667	$1 044 702
44	$1 522 106	$1 196 887	$1 182 995	$1 047 440
45	$1 552 733	$1 206 746	$1 208 020	$1 061 042
46	$1 578 538	$1 216 519	$1 221 946	$1 063 709
47	$1 604 174	$1 226 209	$1 235 674	$1 066 342
48	$1 629 643	$1 235 815	$1 249 207	$1 068 940
49	$1 654 947	$1 245 339	$1 262 550	$1 071 504
50	$1 697 238	$1 255 271	$1 300 435	$1 074 935

Table 12 - LCC of each system

10 MATRIX CRITERIA EVALUATION

The team created a decision matrix in order to visualize a decision-making process.

Ten grading categories were created. Each category had a weight from 1 to 5 - where 1 means the least important and 5 means the most important category.
Points from 1 to 5 were given in categories and then multiplied by a category weight, to reflect its importance. Additionally, points obtained with LEED rating system were added, with a weight equal 1.

Finally, multiplied point values were summed up to indicate total points given to judged system.

Categories considered as most important are: Reliability and Maintainability, due to the location of the building - an isolated island, where any maintenance is difficult.

Maximal number of points possible to achieve in overall analysis was **247**.

Category name	Category weight	WSHP		GHP&CB		WERH	
		Points given	PGxW	Points given	PGxW	Points given	PGxW
Initial Cost	3	3	9	5	15	4	12
Operating Cost	4	4	16	1	4	5	20
Controllability	4	5	20	4	16	5	20
Flexibility	4	5	20	5	20	5	20
Reliability	5	3	15	4	20	4	20
Maintainability	5	3	15	4	20	4	20
Low Environmental Impact	5	4	20	2	10	5	25
Energy Usage	4	4	16	4	16	5	20
Comfort and Health	4	5	20	5	20	5	20
Synergy with Architecture	2	1	2	4	8	1	2
LEED rating	1	34	34	31	31	37	37
Total			**187**		**180**		**216**

Table 13 - Multi-criteria evaluation matrix

11 SELECTED SYSTEM

Team WUT decided that the **Wind Energy Radiant Heating** is the optimal option. It gained the biggest number of points in multi-criteria analysis matrix created by the team and LEED Rating System.

This system showed a 37 % overall cost improvement over the Baseline. This system is predicted to cost $1,07 million over a 50-years period, which is $ 622 303 less than Baseline system, $ 180 336 less than WSHP and $ 225 500 less than the GHP&CB system.

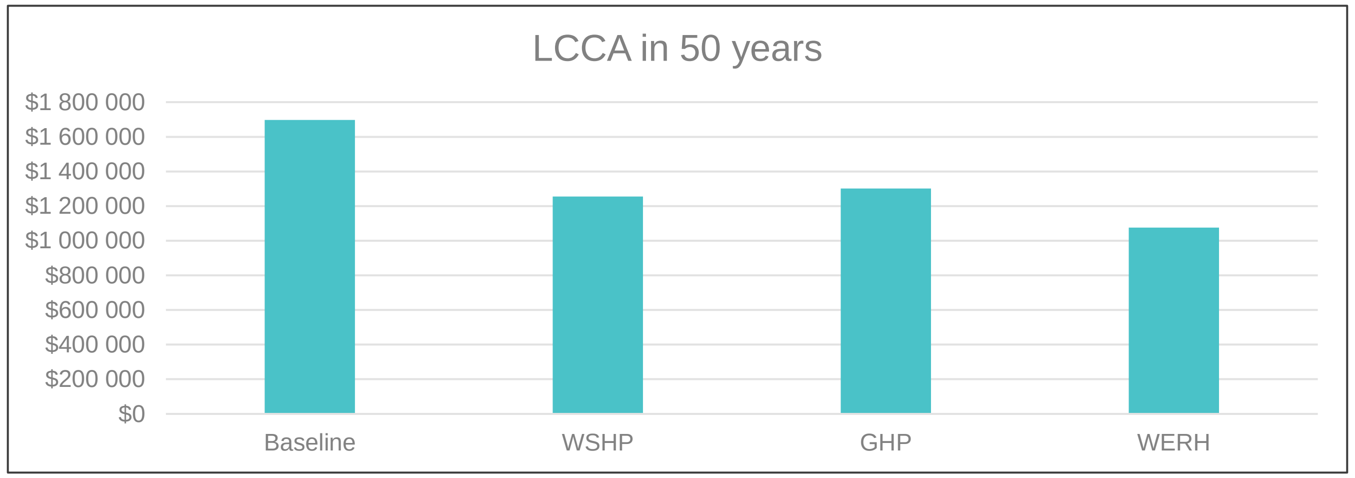


Figure 40 – Total Present Value of all systems selected

This system fulfills all design goals specified by the team. It has the lowest Life Cycle Cost from all considered options. Comfort of Indoor Environment is maintained. System fully meets sustainability requirements - is energy efficient, low-carbon and environmental-friendly. It relies on renewable energy sources - wind and solar power - they are main source of energy for the building, making it almost emission free. The only non-renewable resource consumed in this design is electricity from the power grid, used at the moments of high building power demand. However, it is used in an acceptable amount, in an efficient way, thanks to load shifting and energy accumulation strategy.

12 CONCLUSIONS AND RECOMMENDATIONS

- ✓ The team managed to achieve an expected performance thanks to the usage of modern HVAC systems and following rules of energy conservation and balanced, sustainable usage of natural resources.
- ✓ Using BIM technology was an important part of design process and allowed the team to gather, analyze and manage all data about the designed building.
- ✓ It seems to be important to use analogical analysis like System Benchmarking, because as proven in this report, differences between systems are significant enough to be considered in a design process.
- ✓ It is critical to continue an approach presented in this project during following building life cycle phases - including construction and exploitation. Proper commissioning process must be ensured. Only such approach allows full usage of the proposed design potential.

13 REFERENCES

ANSI/ASHRAE/IES Standard 90.1-2016 - Energy Standard for Buildings Except Low-Rise Residential Buildings

ANSI/ASHRAE Standard 55-2013 - Thermal Environmental Conditions for Human Occupancy

ANSI/ASHRAE Standard 62.1-2016 - Ventilation for Acceptable Indoor Air Quality

ASHRAE Standard 15-2013 - Safety Standard for Refrigeration Systems

ASHRAE Standard 34-2013 - Designation and Safety Classification of Refrigerants

ASNSI/ASHRAE/USGBC/IES Standard 189.1-2014 - Standard for the Design of high-Performance Green Buildings

ASHRAE GreenGuide - The Design, Construction, and Operation of Sustainable Buildings, 2nd edition

ASHRAE Advanced Energy Design Guide for Small to Medium Office Buildings

CEN - EN 15459-2007 - Energy Performance of Buildings - Economic Evaluation Procedure for Energy Systems in Buildings

2016 ASHRAE Handbook - HVAC Systems and Equipment

2015 ASHRAE Handbook - HVAC Applications

2014 ASHRAE Handbook – Refrigeration

2013 ASHRAE Handbook – Fundamentals

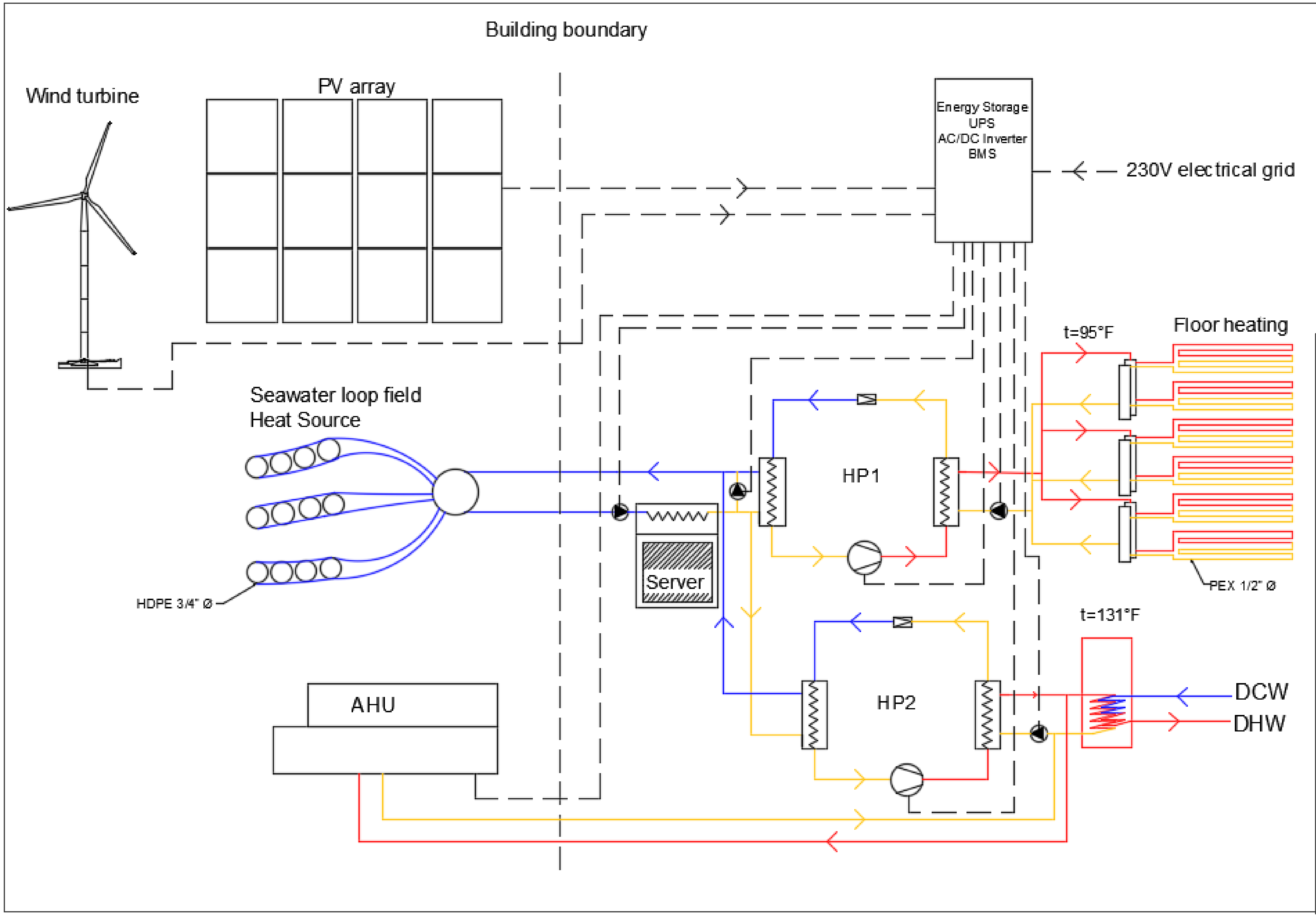
LEED v4 for Building Design and Construction

ASTM E1332-16 - Standard Classification for Rating Outdoor-Indoor Sound Attenuation

ASTM E413 - 16 - Classification for Rating Sound Insulation

ICC IMC (2012): International Mechanical Code

14 APPENDIX A – WSHP SCHEME

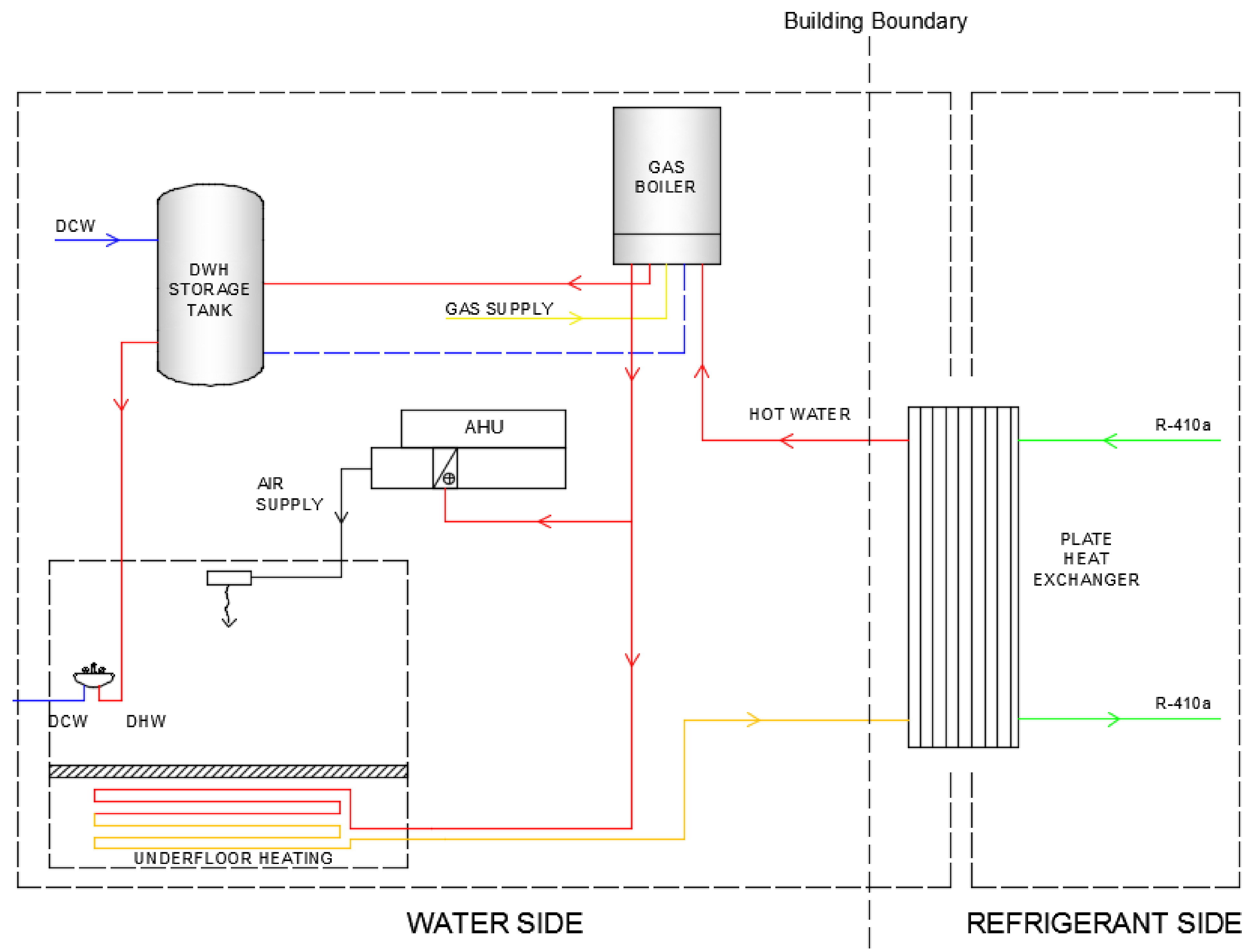


WSHP Equipment Specification

Item	Description	QTY	Specs
1	Heat pump 1	1	40kBtu/h, R134a
2	Heat pump 2	1	25kBtu/h, R410A
3	Floor heating	15 800	PEX 1/2" pipes (feet)
4	Energy Storage Device	1	capacity: 300kWh, peak power 50kW
5	DHW Storage Tank	1	80 gallon
6	PV array	290	4600ft2 area, 13% efficient (290 panels)
7	Wind turbines	3	10kW triple blade wind tubines, 40 ft high
8	AHU 1	1	10 000/10 000 CFM
9	AHU 2	1	15 000/ 16 500 CFM
10	Immersion Cooling	1	4,3 tons cooling load
11	Sea water loop field	15	1500ft HDPE pipe (15 loops)
12	Floor Heating Circulation Pump	1	0,1 HP
13	Bottom Heat Source Pump	1	0,5 hp

Figure 41 – Water Source Heat Pump Scheme

15 APPENDIX B - GHP&CB SCHEME



GHP&CB Equipment Specification

Item	Description	QTY	Specs
1	Heat pump & Boiler Hybrid Device	3	55kBtu/h, R410a
2	Underfloor Heating Piping	15 800	PEX 1/2" pipes (feet)
3	DHW Storage Tank	1	80 gallon
4	PV Array		1300ft2 area, 13% efficient
5	AHU	1	supply: 10 000 CFM exhaust: 10 1000 CFM
6	AHU	1	supply: 15 000 CFM exhaust: 16 500 CFM
7	Immersion Cooling	1	4,3 tons cooling load
8	Underfloor Heating Circulation Pump	1	0,1 HP

Figure 42 – Gas Heat Pump and Condensing Boiler Scheme

16 APPENDIX C - WERH SCHEME

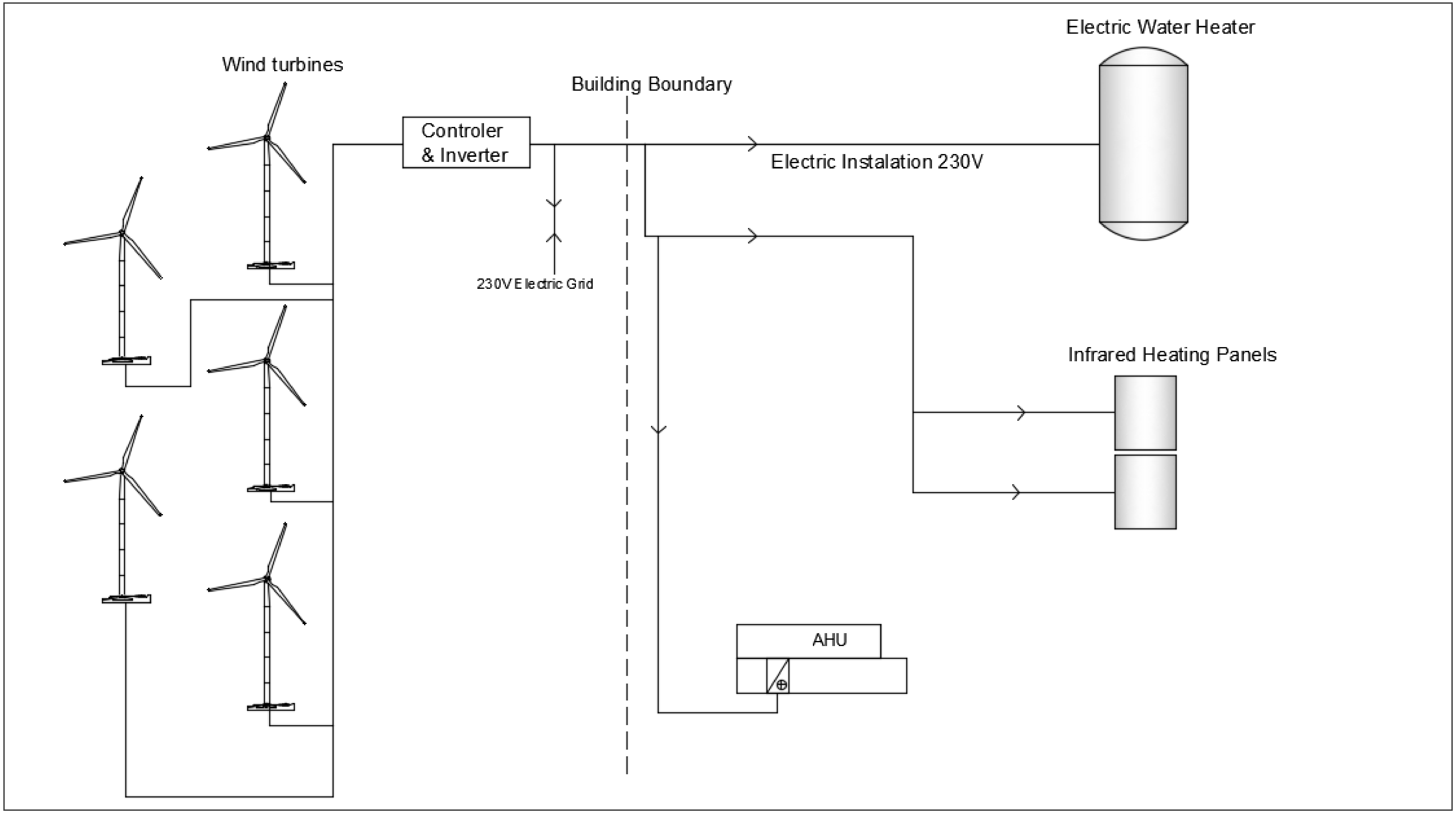


Figure 43 - Wind Energy and Radiant Heating Scheme

17 APPENDIX D – VENTILATION SYSTEM VIEW 1

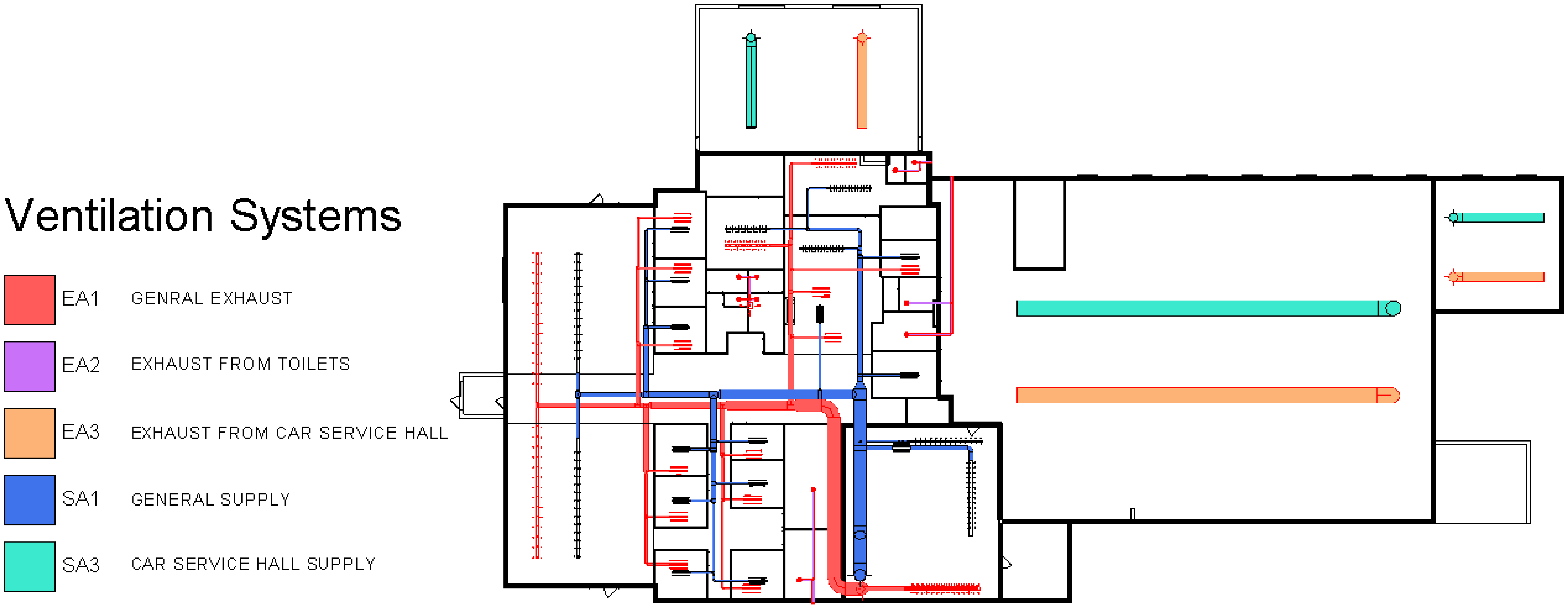


Figure 44 – Ventilation System View 1

18 APPENDIX E – VENTILATION SYSTEM VIEW 2

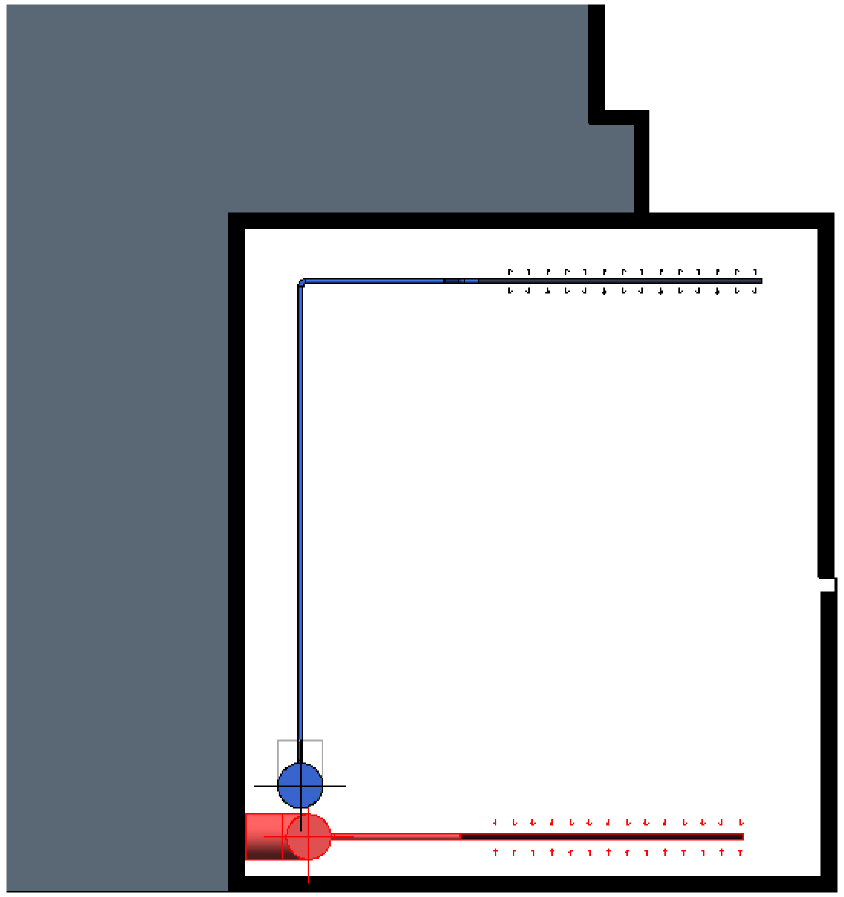


Figure 45 - Ventilation System Schema - Mezzanine level

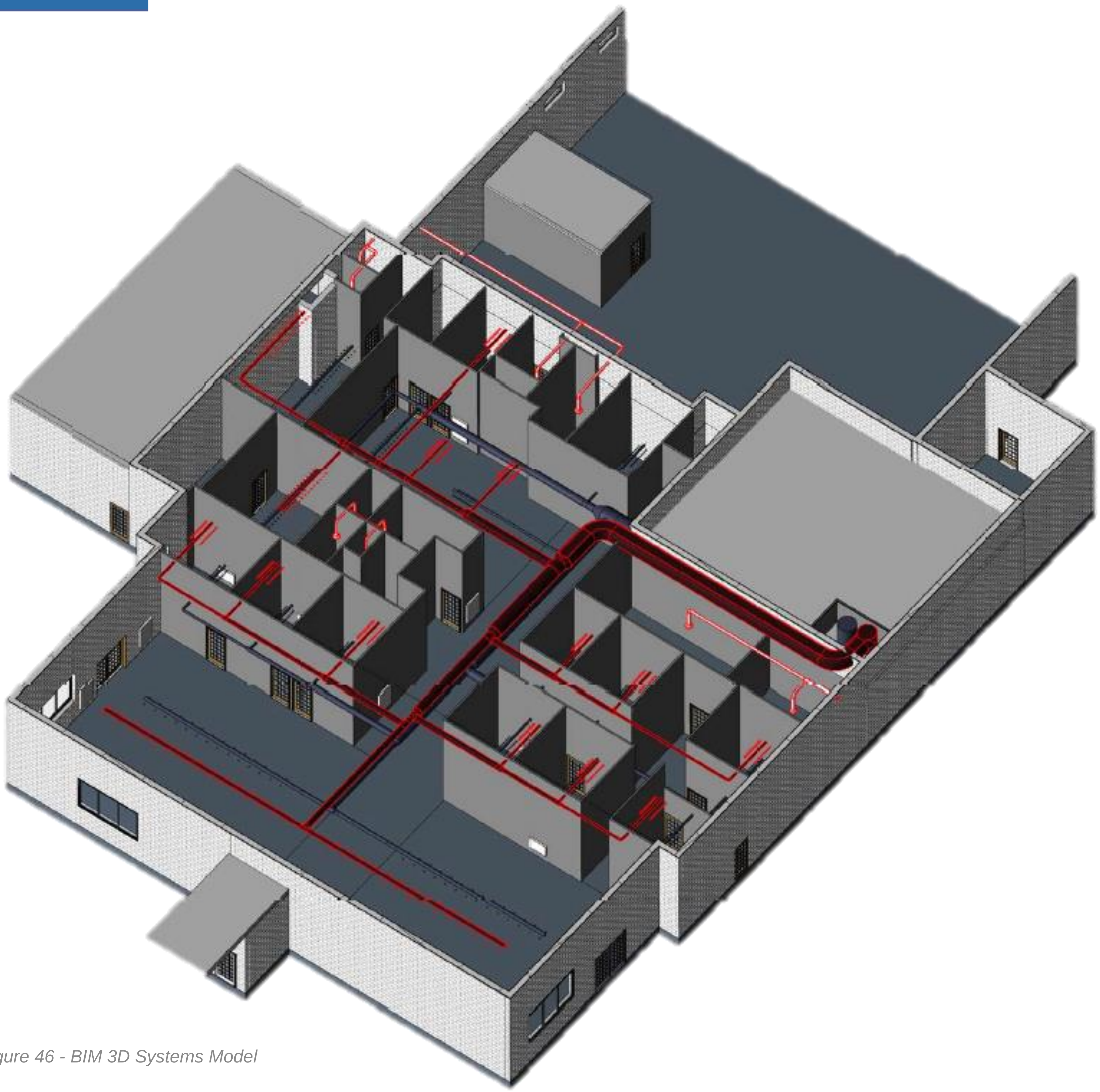


Figure 46 - BIM 3D Systems Model