THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ARCHITECTURAL ENGINEERING

MECHANICAL ENGINEERING OF A COMMERCIAL HIGHRISE WHICH ACHIEVES NEAR-NET ZERO ENERGY, WATER, WASTE AND EMISSIONS

NICHOLAS M. REKSTAD
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Reviewed and approved* by the following:

Moses Ling
Associate Professor of Architectural Engineering
Thesis Supervisor

Richard Mistrick
Associate Professor of Architectural Engineering
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

Faced with the design of a new commercial high-rise—350 Mission—in San Francisco, CA, it was desired that the building operate efficiently and effectively, while minimizing the energy, water, waste and emissions inherent in building operation. In order to design 350 Mission, four main goals were put in place in order to guide the building's conception:

1. Achieve Near-Net Zero Energy, Water, Waste and Emissions
2. Design mechanical, plumbing and fire protection systems which maintain their performance and integrity after a design-level earthquake
3. Utilize Building Information Modeling software, processes and workflows to ensure the highest level of performance possible
4. Design mechanical systems which enhance the aesthetic and participative connectivity of 350 Mission with the surrounding urban ecology

These goals were addressed through the use of *Thermophilic Anaerobic Digestion* in order to generate fuel from municipal sewage and food waste; leveraging *Combined Cooling, Heating and Power* in order to utilize the on-site renewable fuel; utilizing *evaporative cooling* in order to generate cooling water for *radiant chilled ceiling panels* throughout the office spaces in the building; and through utilizing an *AquaCELL Water Reclamation System* in order to reduce 350 Mission's municipal potable water usage.

Through the application of these technologies, as well as through the careful design of supplementary building services, a *100% reduction in building energy*, an *84% reduction in potable water*, a *95% reduction of building waste*, and a *99% reduction in building emissions* was achieved.

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Tyler Dietz	Mechanical Engineer, *Avant*
Chris Coakley	Structural Engineer, *Avant*
Jordan Miller	Structural Engineer, *Avant*
Rebecca Slocum	Electrical Engineer, *Avant*
Katharine Gausseres	Electrical Engineer, *Avant*
RJ Fazio	Construction Engineer, *Avant*
Eric Ripkin	Construction Engineer, *Avant*
Joshua Yacknowitz	Associate Principal, *Arup*
Patrick Regan	Associate Principal, *Arup*
Nigel Marcussen	Associate, *Arup*
Stephane Audrin	Senior Engineer, *Arup*
Moses D.F. Ling	Thesis Advisor, Associate Professor, *Penn State*
Dr. Richard Mistrick	Honors Advisor, Associate Professor, *Penn State*
Dr. James Freihaut	Professor, *Penn State*

Chapter 1

Project Introduction

The AEI Charles Pankow Student Design Competition proposed the challenge of designing a 30-story high-rise building in Downtown San Francisco which addressed the desire to focus on three main areas:

1. Address construction, design and life cycle cost concepts pertaining to a Near-Net Zero building—high levels of sustainability and durability are desired
2. Utilize the existing design as a baseline, and make analytical comparisons with the baseline and alternative options
3. Consider solutions which enable resilience after a design-level seismic event, reducing structural drift to one half of the code-allowed value

This submission was prepared to address the design of 350 Mission. The Submission addresses the design of the building's HVAC systems, heating and cooling plant, energy generation plant, water reclamation system and associated sustainability strategies.

Chapter 2

Project Scope

While the primary focus was designing a building that would operate efficiently while satisfying occupant comfort needs, it was necessary to do this in conjunction with all building delivery disciplines in order to figure out how all aspects of the design and construction could be actualized. This design was completed in conjunction with a multi-disciplinary, integrated design team. The Integrated Design Team developed a set of project principles based on the project requirements and owner requests: ***Performance***, ***Endurance*** and ***Connectivity***.

Performance was defined as the way the building performs throughout its lifecycle. ***Endurance*** describes the resilience of the building over time. ***Connectivity*** describes how the building engages and connects with occupants and the surrounding community. These project goals guided all disciplines though the design process, helping them to produce a fully integrated building solution. The graphic below illustrates how the mechanical design and the desired design outcomes were shaped and guided by these integrated project principles.

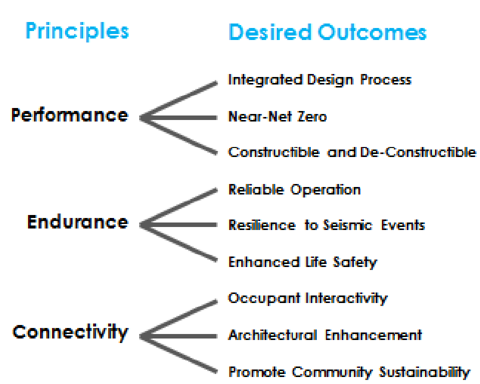


Figure 1. Graphic illustrating goals

Chapter 3

Integrated Project Strategies

The principle of ***Performance*** should be upheld throughout the project's lifecycle—building design and conceptualization included. A high-*performance* design approach was used to design 350 Mission as effectively and efficiently as possible. An integral part of this high-performance design process was the application of BIM software and workflows. BIM software and workflows were leveraged to foster a real-time, holistic approach to building services design that allowed for spatial and data coordination with all disciplines to allow for the most efficient use of time and resources. The concept for the mechanical system was being constantly revised in conjunction with feedback from the other disciplines, so an innovative system for tracking both spatial and engineering data through these revisions was developed. In order to ensure that thermal and electrical data, as well as material quantities were properly tracked by the proper disciplines, the Building Information Modeling software Revit was used to create the building systems within 350 Mission.

Because of its ability to populate physical, spatial models with information, Revit became a crucial component of the design workflow. Information-populated components automatically populated equipment and material schedules; these schedules were then exported to a Tracking Spreadsheet in which team-developed Visual Basic macros utilized comparison algorithms to inform the proper disciplines of thermal, electric and material quantity changes. This ensured that all disciplines were informed in real-time without having to introduce potential human error into the inspection process.

Chapter 4

Context Analysis

Located at the corners of Fremont and Mission Street, 350 Mission will rise 30 stories above street level. The building is primarily comprised of 25 floors of office space; however the project features a double-story lobby, which serves as both the entrance for the building and as a landmark, interactive public space. 350 Mission also contains a restaurant and an underground parking garage.

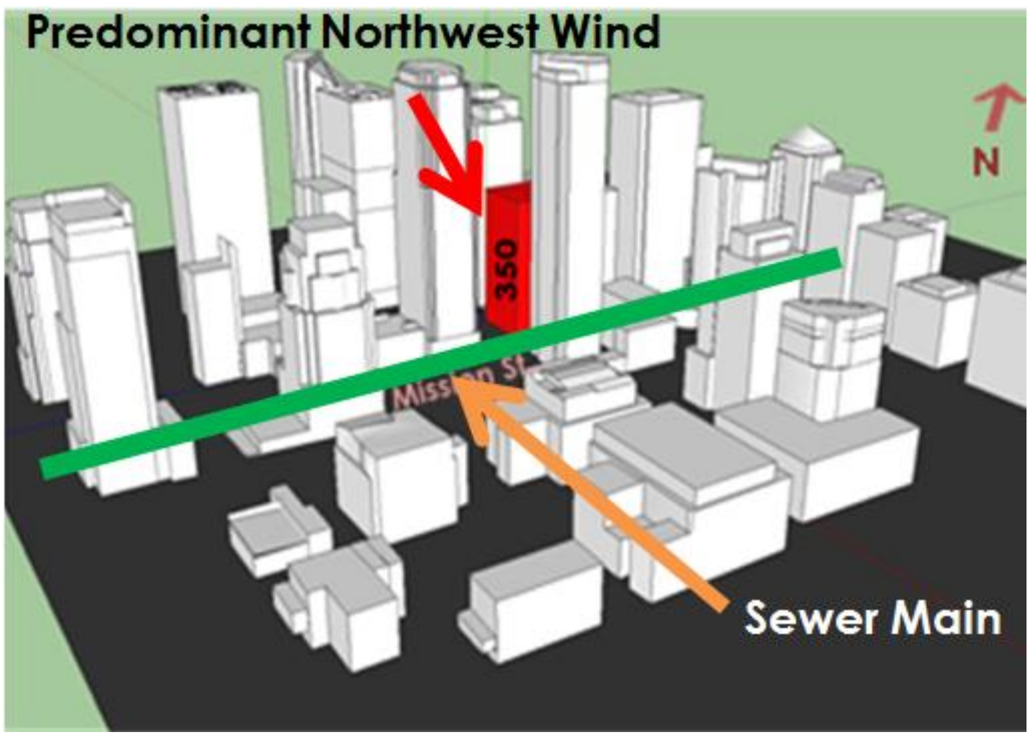


Figure 2. Graphic illustrating 350 Mission's situation within its surrounding environment

350 Mission is located in an area which is populated by residential and business traffic. It is sandwiched between office buildings: 45 Fremont, 50 Fremont, and 50 Beale. Furthermore, the Millennium Tower—primarily comprised of residential, culinary and recreation properties—is located across Mission Street from the site. Beyond, the Transbay

Tower will be located one block south of 350 Mission. The Transbay Tower will be the tallest building in the city upon completion with a roof height of 920 ft and will feature additional office space.

The building is shaded for a majority of the year, given that it is entrenched among many taller buildings. This location also limits the occurrence of frequent, high-speed winds. Utilities service entrances are located along Mission St. and Front St. and the municipal combined sewer runs along Mission Street towards the Embarcadero.

The basis for performative comparison is based on several factors; a ***Baseline Building*** is defined as follows:

- **Energy:** ASHRAE 90.1 Baseline Building as dictated by the Performance Rating Method
  - **Baseline EUI: 31** kBTUh/SF-yr
  - It should also be noted that the ***Actual HVAC Design*** reduced by 31.5%, achieving an **EUI** of **21** kBTUh/SF-yr
- **Water:** Estimated using the LEED Usage Baseline
  - **Baseline Water: 5,237,100** gal per year
- **Waste:** Estimated using CalRecycle office profiles for solid waste and LEED profiles for water waste
  - **Baseline Waste: 6,754** tons per year
- **Emissions:** Estimated using EPA eGRID and Air Quality Planning emissions profiles for primary energy sources for Baseline Energy Consumption
  - **Baseline Emissions: 2,285** tons per year

Chapter 5

Design Theory

It was desired to create systems through the use of BIM which achieved the discipline goals of achieving Near-Net Zero, withstanding a design-level earthquake, and enhancing connectivity with the surrounding community. The following design theory was formulated, which shaped how mechanical systems were conceived and thereby shapes the format of the following narrative:

1. **Reduce Resource Demand**—because there is no *entirely* clean way of consuming resources, minimizing 350 Mission's thermal, electrical and water loads through *passive*, *active* and *participative* means was desired—IES Virtual Environment was used to parametrically model proposed ideas
2. **Produce Resources**—in order to enhance the environment in which it resides, 350 Mission was designed to *draw fuel from the environment in which it resides*
3. **Efficiently Apply Resources**—in an effort to minimize 350 Mission's environmental footprint over the course of the building lifecycle, the most *efficient* and *seismically-resilient* application of the site-generated resources was designed

This design theory created a clear step-by-step roadmap of how to create 350 Mission as a building which is not only efficient, sustainable and seismically-resilient, but as a structure whose presence educates and enriches its community. Below, the aforementioned design process will create the narrative of the systems designed for the competition.

Chapter 6

Resource Demand Reduction

Maintaining thermal comfort and generating electricity consumes resources. Creating potable water in wastewater treatment facilities requires large quantities of primary energy and building waste also consumes a largely diminishing quantity—*space*. Buildings create a demand for finite resources and, in doing so, release emissions which contribute to environmental degradation.

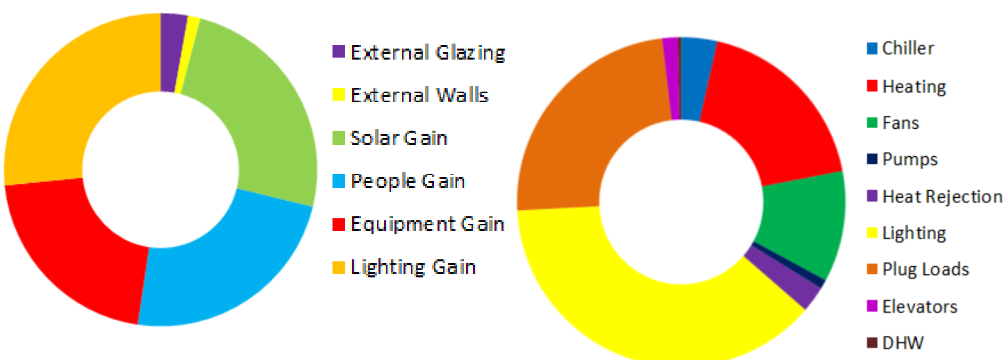


Figure 3. Graphs showing the load breakdown and major energy end-uses of the baseline model

A series of strategies were formulated in order to reduce primary energy and environmental resource requirements. Before devising demand reduction methods, IES Virtual Environment was used to analyze a baseline building to determine the major loads on the building. These analyses were used in order to guide the team towards devising a load reduction strategy. The graphic below illustrates the load breakdown which guided load reduction strategies.

Based on the load and energy studies, the following strategies were developed in order to reduce 350 Mission's need to utilize resources:

- **Optimize the building enclosure**
  - It was desired that the enclosure should allow natural light into the space while minimizing solar gain
- **Reduce water use**
  - Through fixture selection, the demand for potable and non-potable water can be reduced
- **Collocate refuse facilities**
  - By placing recycling stations near workstations and locating refuse containers in the core of the building it will become more convenient to divert from landfills
- **Create an energy-efficient workstation**
  - Because the building is primarily office space, an office workstation which minimizes sensible heat gain and electricity usage through task-ambient lighting and a Thin-client Virtual Desktop infrastructure was designed

In the following sections, the detailed building enclosure optimization process is elaborated upon. For the other Demand Reduction strategies, see the appendices and narratives referenced above.

6.1 Envelope Optimization

The building envelope provides shelter from the exterior environment and is, in a large way, what makes buildings a necessary structure in society. The envelope also consumes no energy during the building's operation, so a high-performing façade can passively reduce energy demand throughout the building lifecycle. It was realized that he building envelope also resides at the intersection of almost every discipline involved in a building's design. An enclosure which enabled 350 Mission to accomplish the following was desired:

- Withstand design-level seismic forces
- Allow for easy and expedient construction
- Create an independent architectural identity within San Francisco
- Enable optimal energy performance throughout the year

6.1.1 Façade Studies

In addition to creating a façade which engaged the surrounding environment, it was desired to optimize the façade in order to minimize overall energy usage over the course of the year while allowing the building envelope to maintain high levels of seismic resilience during a design-level earthquake.

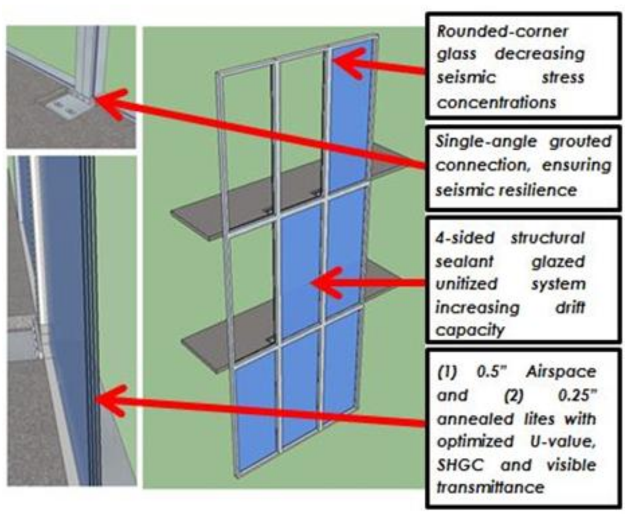


Figure 4. Graphic showing the different components of the curtain wall facade

It was decided that an all-glass curtain wall presented constructability, seismic and natural lighting advantages. IES Virtual Environment and DaySim were used to analyze the thermal energy and lighting energy advantages of three different curtain wall options which met the Movement and Tolerances Requirements specified by the project's seismic constraints, the results of which are shown below. This analysis was carried forward as a part of the ASHRAE 90.1 Performance Rating Method analysis necessary to justify our 350 Mission versus a Baseline Building.

Table 1. Control and variation parameters analyzed during the facade study

Assembly Type	Assembly U-value [BTU/hr-SF-F]	SHGC	VT
Viracon Triple Pane	0.17	0.25	41%
Solarban 60	0.4	0.39	70%
Guardian 62/27	0.35	0.27	64%

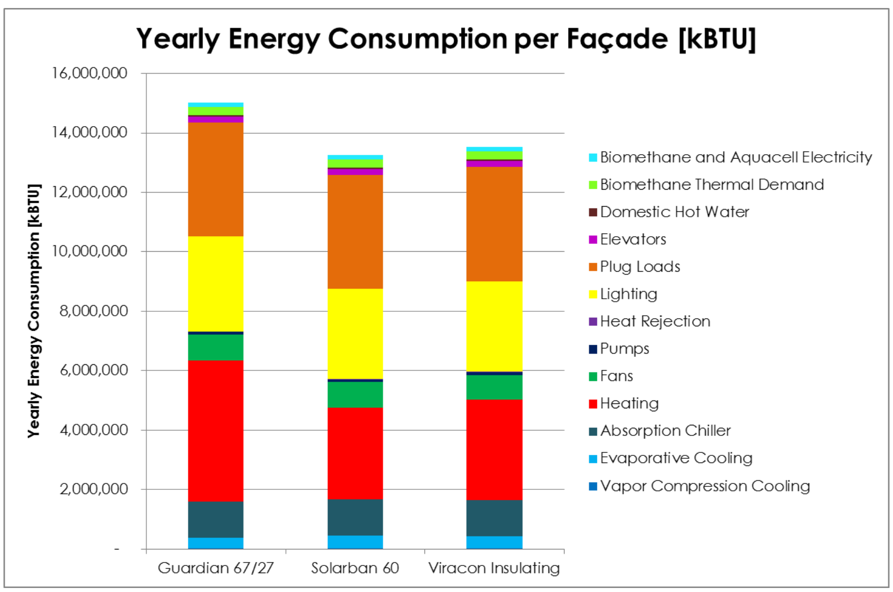


Figure 5. Graph showing the results of the glazing study; it was clear that Solarban 60 was the best choice

It can be shown from the IES Virtual Environment and DaySim studies that the ***Solarban 60 Double-pane, Air-filled glazing*** makes the most sense because its lower SHGC allows for higher winter solar gain to reduce heating energy throughout the winter, while only minimally raising cooling energy—this is due to the very efficient cooling strategy discussed in Section

8.2.2.1. Solarban 60 also presented lighting advantages, presenting the highest daylighting performance of the three glazing types.

6.1.2 Roof Design

Because of the low percentage of the building which is in contact with the roof, thermal insulation was not deemed to be a major design constraint. Acoustical insulation, however, was decided to be the driving consideration for the roof because of the roof-mounted mechanical equipment. **NC 35 was maintained in the office space below** using a roof composed of concrete poured over a metal deck with a layer of insulation to provide the necessary transmission loss. A roof with a high **Solar Reflective Index of 92** was also selected for the roof to minimize the Urban Heat Island Effect.

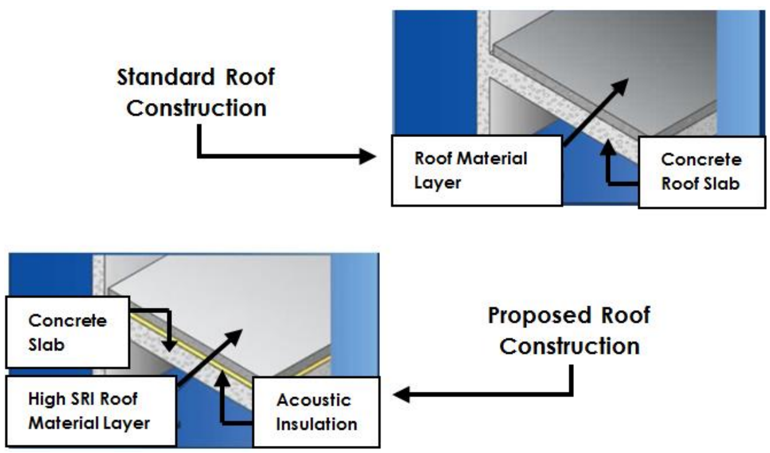


Figure 6. Graphic illustrating the standard roof construction compared to the proposed roof construction

Another code requirement of the San Francisco area is the elimination of surface runoff of rainwater. Based on 100 year storm data for San Francisco, four roof drains of 5" diameter were placed in strategic locations along the roof to capture all possible rainfall without little risk of overflowing out onto the roof surface. After harvesting the rainwater, it is stored in a tank near the top of the building that is connected into the plumbing piping system. This rain water is staged to primarily service the top five floors of 350 Mission. In the event that the tank is not sufficiently full, the primary plumbing system is tied into the top five floors in order to meet demand.

6.1.3 Demand Reduction Takeaway

After implementing the strategies mentioned above, it was shown that the **space cooling loads were reduced by 7% and the heating loads were reduced by 8%** relative to the ASHRAE 90.1 Baseline. It was also shown that **potable water demand was reduced by 34%** and **landfill waste was reduced by 95%**. It will become apparent after discussion on Resource Generation methods and Resource Application methods, the extent to which this reduces overall building emissions.

Chapter 7

On-site Resource Production

As illustrated in the Site Analysis, 350 Mission has minimal access to solar and wind energy. CFD simulations on the surrounding five blocks showed that the wind generation potential of the site was inadequate due to the taller surrounding buildings. Initial studies also showed that, based on the shading of surrounding buildings over the course of a Typical Meteorological Year, roof-mounted photovoltaic panels would only produce a theoretical maximum of 81,700 kWh.

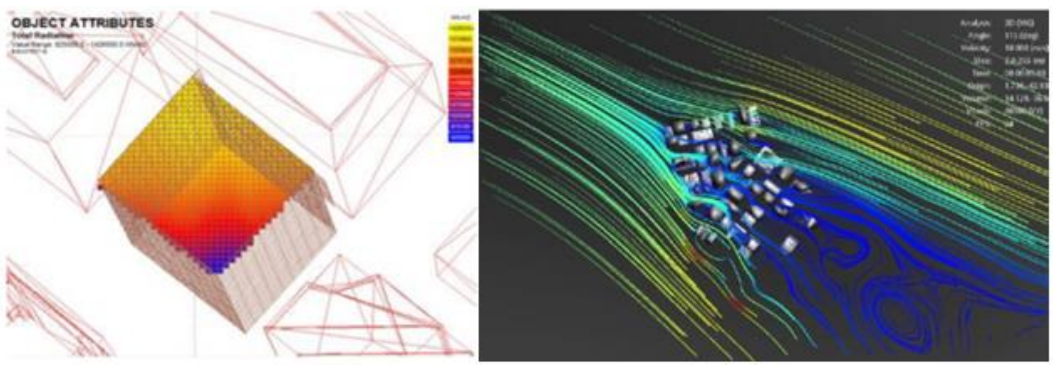


Figure 7. Graphic showing the results of the site studies, illustrating need for non-conventional energy generation

Installing PV panels was deemed to be inadequate for our site because of low generation capacity, and because the off-shore manufacturing which makes them economically-competitive has been known to pollute riverine ecologies adjacent to manufacturing facilities.

The design then turned to biology in order to examine how energy is transferred within natural processes and it was found that, within ecologies, the waste of one biological process is a source of energy input for another. It was realized that, within the urban ecology of San Francisco, large quantities of sewage and food waste are present and contain a large quantity of embodied energy.

7.1 BioMethane Generation

Generating BioMethane from raw sewage and organic compost is an energy generation method which has had success in the wastewater treatment and solid waste management industries, respectively. There has also recently been a high-rise installation in Osaka, Japan in the Abenobashi Terminal Building. Anaerobic digestion—the process by which methane is created from oxygen-deprived organic matter—is comprised of four phases, Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. For an explanation of the process by which BioMethane is generated, see Appendix E.

This BioMethane can be harvested and then stored for use in combustion. During Methanogenesis, either Thermophiles—bacteria which thrive in high heat—or Mesophiles—bacteria which thrive under normal temperatures—break down the organic matter. Thermophilic digestion creates bio-methane at a rate up to three times faster than Mesophilic digestion and is the process used in 350 Mission. This digestion condition requires that the digested solids be maintained between 120 and 135^{F}, creating a consistent thermal load which, as illustrated later, will ensure that the building's combined heat and power system utilizes its fuel efficiently. Another advantage of Thermophilic digestion is that it neutralizes pathogens in the digested solids, rendering the material in the anaerobic digesters harmless and odorless.

It was found that one of the main veins of the city's combined sewer system runs via Mission Street to the Embarcadero. This presents a large wastewater resource to the building because 15,000,000 gallons per day flow through this sewer main, as reported by San Francisco's Wastewater Enterprises Division. Scalping wastewater from municipal sewer systems is a renewable energy scheme becoming increasingly-popular in Australia and is allowed in San Francisco under the condition that a Memorandum of Understanding is signed between the San Francisco Public Utilities Commission and the owner of 350 Mission. The Mechanical Systems

Team has decided to deploy it for three main reasons other than the fact that it presents fuel-creation opportunities:

1. Harvesting water from the sewer allows for the reclamation of water resources from the solids-separated wastewater for non-potable water end-uses in the building
2. Wastewater mining allows 350 Mission to reduce the strain on San Francisco's overtaxed combined sewer system, reducing odor problems downstream at the Embarcadero sewer vents
3. Scalped wastewater, once passed through solids separation, can be used as a heat extraction or rejection source for the water-to-water heat pumps in the building

It was also found that the San Francisco sanitary service provider Recology mandatorily collects compostable food scraps separately from landfill and recycling waste. Recology also provides preprocessed food waste to wastewater treatment plants in the Bay Area free of charge for use in their anaerobic digesters. The proposed design intends to engage in a similar arrangement with Recology in order to collect municipal food waste on-site in order to slurry the mixture and use it in the BioMethane System.

350 Mission will receive **32 tons of food waste per day** from Recology, which is relatively small compared to the 600 tons per day that Recology collects in San Francisco. It was decided that food waste would be the primary source of fuel generation for the plant because the energy density of food seven times higher than that of sewage; when humans digest food they remove a large quantity of the embodied energy. This means that the quantities, therefore the auxiliary energy overhead, of digesting the food waste is significantly lower than solely digesting sewage.

It was decided that a hybrid sewage/compost digestion system would be the most worthwhile investment because of the ability to reclaim water from the sewage in addition to being able to reject heat into the solid-separated wastewater, saving cooling tower fan energy.

By **scalping wastewater from the municipal sewer system at a rate of 1,500 gpm** and **collecting compost at a rate of 32 tons per day**, **BioMethane is generated at a rate of 72,300 ft^3 per day**. The mathematical models used to determine methane production quantities were sourced from research journals published by the *Slovenian National Institute of Chemistry*. These models were crucial in determining residence time, space requirements and system output. Because the generated methane volume is largely dependent on residence time, spatial constraints are introduced. These space constraints result in a **residence time of 10 ½ days**, which was selected because of the space requirements of the digestion tanks, gas conditioning equipment and other associated supplementary systems.

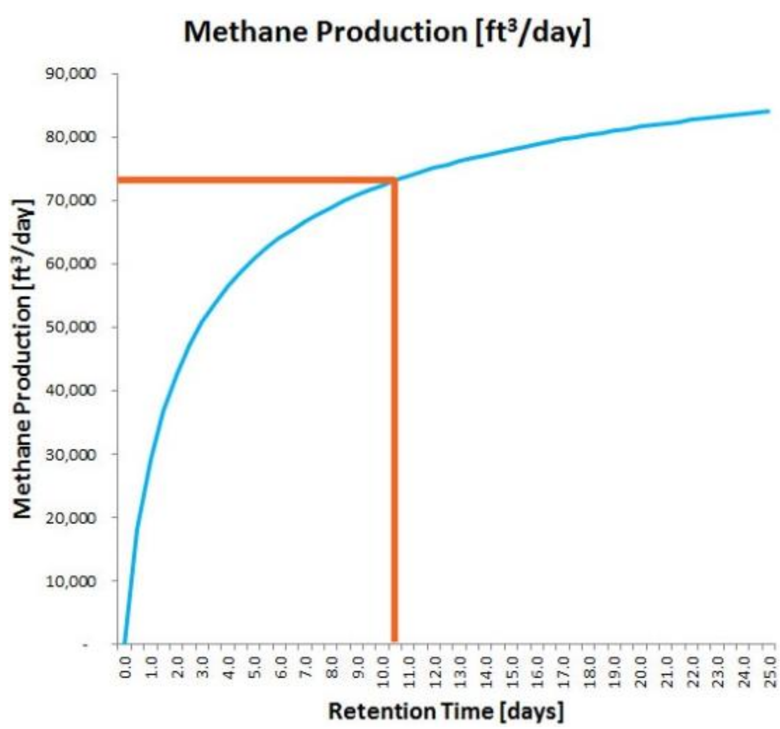


Figure 8. Graph showing methane production vs. residence time

Generating fuel on-site allows for the majority of site-utilized energy to be produced without paying for fuel. Typically cogeneration processes require natural gas to be purchased, limiting the economics of the system. After a Life Cycle Economic Analysis, considering fuel price escalation rates as well as projected discount rates, it is shown that the proposed biomethane cogeneration plant (*including the CHP prime mover*), costing **between $1,147,000 and $2,170,000** will have a total discounted payback period of **2 ¾ to 5 ¼ years** without any grants or government incentives. These figures were calculated according to the sensitivity analysis on the digestion facility costs. It was found that, over the course of a typical year, **2,715,600 kWh of electricity are generated**. This is enough electricity to bring 350 Mission's **EUI to -0.02 kBTU/yr-SF**. Over the course of a 50 Year Life-cycle, the BioMethane System **saves $13,646,200** and **52,100 tons of CO_2** emissions. This total is equivalent to the lifecycle carbon sequestration potential of over **114,300 trees**.

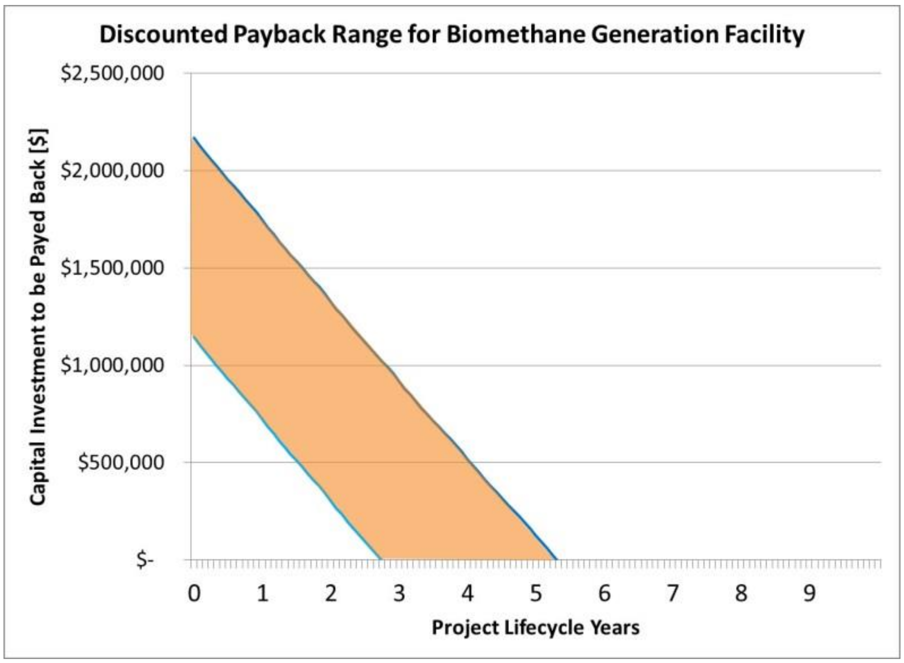


Figure 9. Graph showing the sensitivity analysis on the power generation system payback

Because the conversion of food waste and sewage to methane is a crucial component of the design for 350 Mission, a physical design for the BioMethane Plant was conceived and constructed it in Revit. This allowed the plant to be arranged spatially as well as allowing for the coordination of the outgoing utilities with the rest of the design team. The plant's Revit model is shown below.

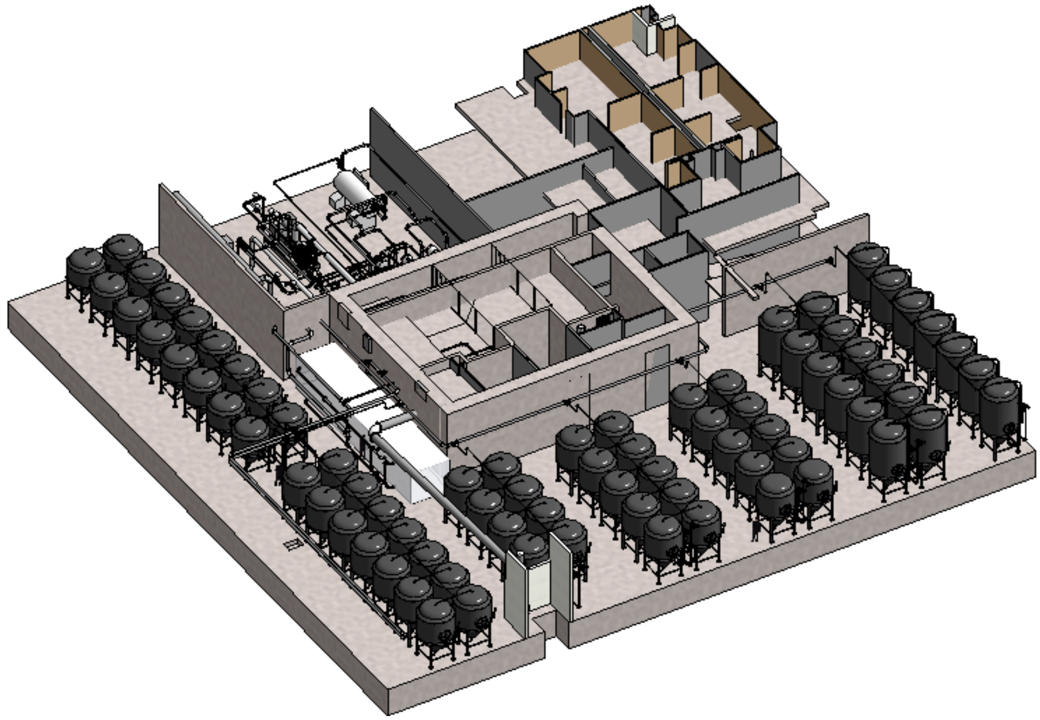


Figure 10. Isometric view of the modeled BioMethane Facility

The design of this facility is a result of integrated collaboration. In order to generate renewable heat and electricity on-site, space needed to be made for the fuel generation system, due to the fact that the fourth-level sub-basement had an average floor-to-floor height less than 6'. The overall weight of the building's structure was able to be reduced in order to reduce loads on the foundation. This allowed the thickness of the Mat Slab to be reduced by 4', enabling the floor-to-floor height to be increased such that the facility would be able to fit in the basement, seismically protecting it from earthquake accelerations.

7.2 Combined Heat and Power

The BioMethane generated from the process discussed above is then combusted in a 310 kW IC Engine (60 Hz at 1800 rpm) in order to generate electricity. The thermal energy generated from jacket cooling water as well as from the exhaust gas is captured and utilized in order to maintain thermophilic temperatures in the anaerobic digesters as well as for heating and absorption cooling.

An IC Engine was selected over alternatives such as microturbines because of higher resilience to H_2S, better part-load efficiency, better load-tracking, lower O&M costs and a better $/kW$_e$, as illustrated by a report published by the EPA.

Though normal Combined Heat and Power (CHP) facilities which purchase natural gas must typically track thermal loads in order to gain an emissions advantage over Separate Heat and Power (SHP) systems, the BioMethane-fueled CHP system designed for 350 Mission is able to justifiably produce electricity at full output constantly due to the characteristics of its fuel source—sewage is anaerobically digested at local wastewater facilities and is either flared or used in CHP processes; the same is true of Recology's compost—landfill gas is typically flared in San Francisco except for the small amount distributed to the CHP-utilizing wastewater plants. Essentially, the fuel *has* to be combusted no matter what, so it is desired that 350 Mission add value to the waste stream by harnessing it for energy.

With that being said, 350 Mission utilizes thermal energy well throughout the year. Studies to analyze the Primary Fuel Utilization Efficiency (PFUE) of 350 Mission's CHP system compared to Separate Heat and Power (SHP) were undertaken under a range of electrical grid and power generation efficiencies in order to obtain the objective performance of the system, though almost all of the primary energy used in 350 Mission was renewably generated on-site. It can be shown below that, for a range of electrical grid performance characteristics, CHP outperforms SHP for all but the lowest thermal loading conditions, assuming the highest performing electrical grid possible; for average grid conditions, CHP outperforms for the entire year, as illustrated below.

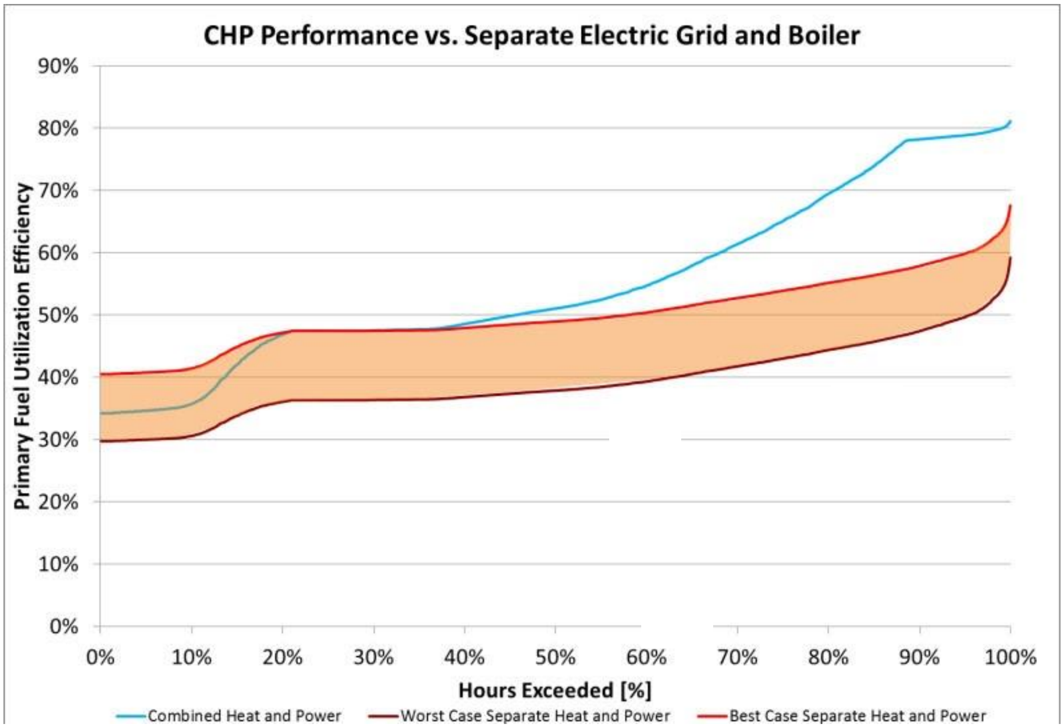


Figure 11. Graph illustrating the PFUE for 350 Mission's CHP system vs. Grid SHP for varying conditions

Because of the free fuel, as discussed in Section 7.1, the overall discounted system payback (including the BioMethane generation plant) is between **2 ¾ to 5 ¼ years** without any grants or government incentives. Over the course of the year, **over 2,715,600 kWh** of electricity and **119,000 therms** are produced, **offsetting 350 Mission's grid energy usage of *399 MBTU of natural gas and 924,000 kWh of electricity*.**

7.3 Blackwater Recycling

It was also realized that repurposing greywater and blackwater would reduce the resources required by the municipalities because water intended for non-potable end-uses can then be treated to a lower, less energy-intensive standard than that which typically flows through domestic water pipes. To achieve this, an AquaCELL Blackwater Purification System is utilized in order to generate water for toilet flushing and cooling tower makeup.

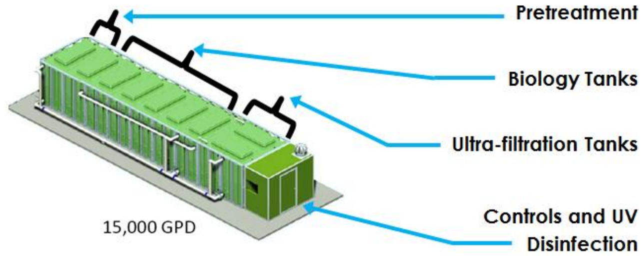


Figure 12. Illustration of the AquaCELL system designed for 350 Mission

The **AquaCELL is sized to treat 14,115 gpd at a low 7.3 W/gal**; the module with a 15,000 gpd capacity (*38' x 8' x 7'*) is selected in order to meet this demand. This results in an **84% reduction in municipal potable water use** for a **price of $1,210,000**.

Chapter 8

Efficient Resource Application

In order to make 350 Mission as resource-efficient as possible, space design schemes which allocated site-generated resources as effectively as possible were used. Load-handling strategies which minimized the need for thermal input beyond that which is produced from bio-methane were employed. Systems and design schemes are divided into **Plant** and **End-use**. The end-uses of the site-generated energy are discussed below and an overall schematic of the design is shown below.

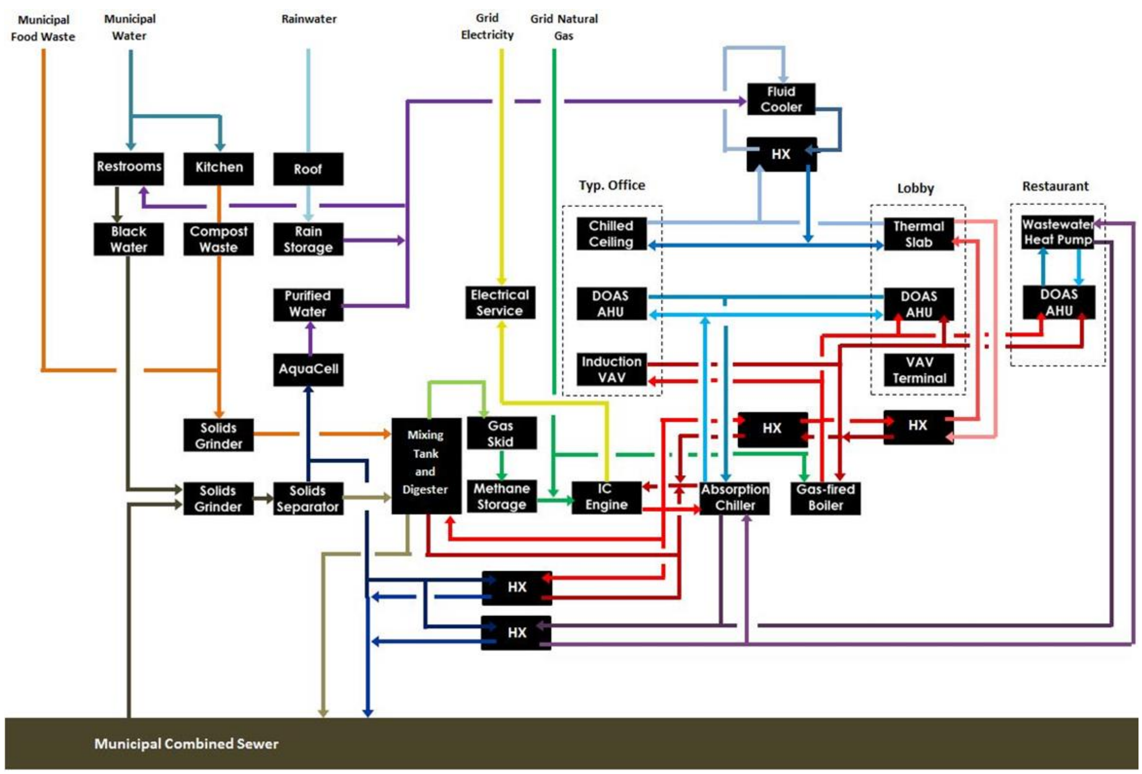


Figure 13. Overall schematic of the building's mechanical systems

8.1 Efficient End-uses

350 Mission's mechanical systems are discussed below in terms of Supply and Demand. The demand side of the mechanical systems for 350 Mission includes the detailed design of the building's Upper and Lower Lobby, Restaurant and Typical Office Floor. The design for each space will be discussed in depth below:

Table 2. Table illustrating the space design conditions for the detailed design spaces in the building

Space Design Conditions	Cooling			Heating	
	T_{db}	$RH_{\%}$	$T_{drift,cooling}$	T_{db}	$T_{drift,heating}$
	[F]	[%]	[F]	[F]	[F]
Upper / Lower Lobby	76	55	78	70	68
Restaurant	75	50	77	72	70
Typ. Office Floor	76	55	78	70	68

Table 3. Table showing the outdoor design conditions for San Francisco

Outdoor Design Conditions		
Summer Dry Bulb	78.0	[F]
Summer Wet Bulb	62.0	[F]
Winter Dry Bulb	37.8	[F]

8.1.1 Upper and Lower Lobby

Because of the architecturally-significant nature of the lobby, great care was taken to protect the integrity of the architect's vision for the space. A key goal of the architect's was to visually and spatially connect 350 Mission with the Transbay Center across the street. In the plans, the corner of the lobby which resides at the corner of Mission and Fremont is open to the air. The space conditioning strategy considers the preservation of the architect's vision for this corner, in addition to the preservation of the aesthetic integrity of the space.

Table 4. Table showing the loads for the lobby space

Lobby Peak Load Summary					
Space Sensible	499,946	[BTUh]	Space Heating	197	[MBH]
Space Latent	193,444	[BTUh]	Fresh Air	14,198	[CFM]

HVAC Systems

It was realized that space conditioning should not be done through a forced air system due to the fact that potentially-unsteady air movement patterns through the opening could compromise the effectiveness of a forced air system's ability to deliver thermal comfort. It was decided that a thermally-active radiant slab would fit the space conditioning needs of the lobby most effectively. By relying on primarily radiant heat transfer, view-factor becomes the most important heat transfer parameter. This allows for thermal comfort despite potentially-dynamic air conditions at the lobby's open-air entry. By utilizing a hydronic system to provide thermal comfort in the space, the pressurization can be decoupled from the space conditioning system.

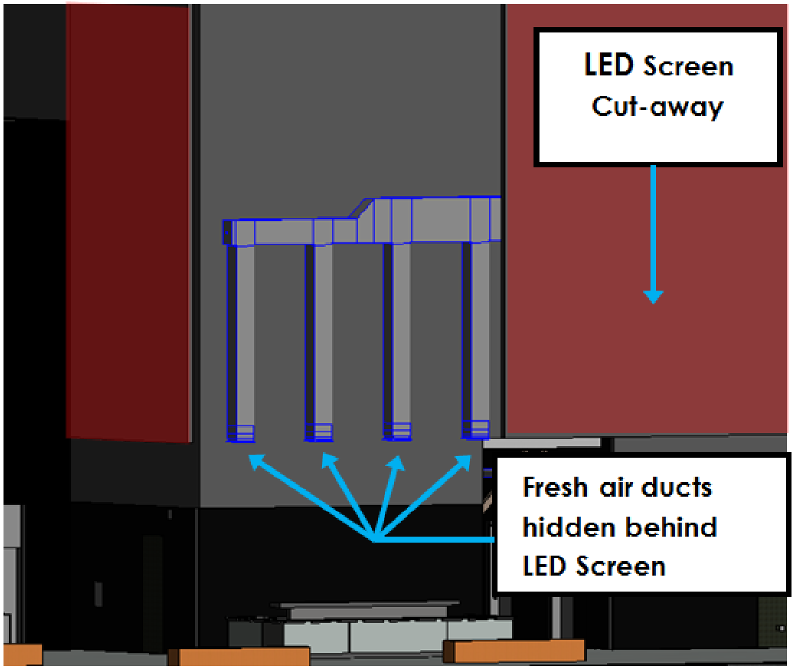


Figure 14. Graphic showing that HVAC elements are hidden from view in order to preserve the sleek appearance of the lobby

Cooling Season

The thermal slab chilled water supply will be supplied by roof-mounted heat exchanger-coupled cooling towers at a design temperature of 67F. These fluid coolers will supply High Temperature Chilled Water throughout the cooling season. A typical concern with chilled slabs is that condensation can occur, causing puddles and bacterial growth, however the design for 350 Mission avoids these concerns due to a 10.2^{F} difference between average slab surface temperature and the design dew point.

Table 5. Table illustrating slab cooling design conditions

Thermal Slab Cooling Parameters			
V_{design}	1.5 gpm	ΔT	3.3 F
$T_{CHW,in}$	67.0 F	$T_{avg,surface}$	68.9 F
$T_{CHW,out}$	70.3 F	$Flux_{Cooling}$	14.6 BTUh/SF

Heating Season

During the heating season, a plate-and-frame heat exchanger will provide heat transfer between the IC Engine's waste heat hot water loop—the temperature of which (200^{F}) is too hot for radiant floor applications—and the radiant floor's Low Temperature Heating Hot Water (LHHW). The cooling and heating design conditions for the thermal slab are illustrated in Tables 5 and 6, respectively.

Table 6. Table illustrating the design conditions for the thermal slab heating system

Thermal Slab Heating Parameters			
V_{design}	1.5 gpm	ΔT	6.9 F
$T_{HW,in}$	93.0 F	$T_{avg,surface}$	89.0 F
$T_{HW,out}$	86.1 F	$Flux_{Heating}$	37.0 BTUh/SF

Lobby Pressurization

Because 350 Mission is a high-rise building, it was recognized that counteracting the stack effect during the cooler months of the year would be important. Winter design conditions result in a maximum **stack pressure differential of -1.23 in wg**, at the lobby level. This pressure difference was recognized to be a large design concern in the lobby space due to the large opening on the southwest corner of the lobby, it was estimated that this pressure difference could allow **up to 7,500 CFM of unfiltered street-level air** into the lobby space, displacing it throughout the upper office levels.

Pressurizing the space in an energy efficient manner became a key focus for the team for the design of this space. Exhaust air from the AHU serving the first five floors is used to pressurize the lobby without having to expend extra thermal energy to condition pressurization air; this is possible because the office levels are Class I spaces and the transfer and recirculation of their air is permitted under Title 24. Pressurization air is supplied alongside the Upper Lobby's ventilation air through a pressurized plenum above the second floor of the lobby as shown below.

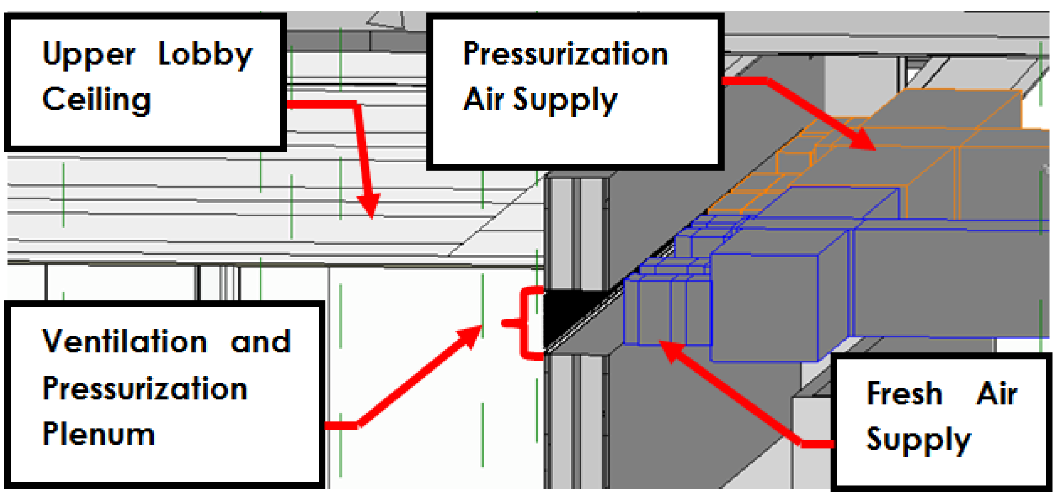


Figure 15. Picture showing the ventilation air and pressurization air in a plenum above the restaurant entrance

The pressurization of the lobby was considered to be very important for the maintenance of good thermal comfort and indoor air quality. Contaminants enter the space and are driven upwards through the building any time that the outdoor temperature drops below the indoor set-point. The mechanical system team desired to avoid street-level infiltration due to the large number of contaminants and pollutants which would enter the space from the buses, cars and other means of transportation present at the Transbay Terminal. CONTAM Multi-zone airflow analysis illustrated that allowing stack infiltration to occur so close to a major transportation hub would increase the *aggregate cancer risk* in 350 Mission by over 41%. The prevention of contaminant migration is done in order to preserve the health of the employees who would be in the lobby for extended periods of time, as well as the health of other occupants throughout the building. Combatting stack infiltration additionally helps to prevent the constant cleaning of lobby surfaces which would be necessary if infiltration was allowed to occur.

Plumbing Systems

The main plumbing design element of the lobby space is the electro-chromically glazed interactive restroom. This space educates visitors and passersby on how the sanitary systems of 350 Mission not only contribute to reducing 350 Mission's municipal water use, but function as a part of a self-integrated energy generating system within the building.

Design for Resilience and Life Safety

Endurance and operation during a seismic event was an important factor when designing the lobby mechanical systems. The lobby space utilizes a deluge sprinkler system a smoke evacuation system in the case of a fire emergency. The smoke system exhaust system will use the exhaust method outlined in *Section 909.8* of the *California Fire Protection Code*. Smoke is exhausted through a large return at the top of the space which will maintain tenable conditions for 20 minutes while also keeping the smoke at least 10 feet above the highest occupied surface, which is the second story restaurant space. The air that is typically exhausted into the lobby to maintain a positive pressurization will then be used as make-up air in the case of a fire emergency.

8.1.2 Restaurant

350 Mission features a premier destination-style restaurant, the exact details of which are not specified in the competition program. It was opted to treat the restaurant, kitchen and supporting areas as tenant fit-out spaces, providing future occupants with the means to mitigate sensible and latent loads and properly provide exhaust and makeup air.

Table 7. Table illustrating loads for the restaurant

Restaurant Load Summary					
Space Sensible	169,433	[BTUh]	Space Heating	79	[MBH]
Space Latent	56,017	[BTUh]	Fresh Air	6,862	[CFM]

HVAC Systems

The restaurant features a dedicated 100% Outside Air Unit which is exclusively supplied by a water-to-wastewater heat pump. This dedicated system was desired because it allows the restaurant to operate on independent hours efficiently. For details on the design of the water-to-wastewater heat pump, refer to Section 8.2.1.3.

The 100% Outside Air Unit supplies the restaurant and supporting spaces in order to mitigate the high latent loads. Because of these latent loads, an all-air space conditioning strategy was desired over using a radiant system. This 100% outside air system was chosen over using a recirculating air handler in order to take advantage of the coolth of San Francisco's climate, which has less enthalpy than recirculation air would have for a majority of the year.

Plumbing Systems

The plumbing system for the restaurant will be accounted for in the design for the rest of the system. Cap offs and other extensions are installed within the main riser to allow for the restaurant to tie in as necessary.

Design for Resilience and Life Safety

The restaurant space will be designed according to code for fire protection and seismic resiliency once all information is known about the space.

8.1.3 Typical Office Floor

Because the office floors account for over 75% of the total building area, it was realized that energy conservation measures on the office floors would have the largest return for the overall project. An initial load study on the 20th floor—the level which was decided to be our "typical office floor"—illustrated that the majority of the office floor would need year-round cooling, however there would be periods of the year which required perimeter space heating. An energy-efficient scheme in order to achieve our goal of minimizing energy consumption while satisfying both conditions, as discussed in the following sections.

Table 8. Table illustrating the loads for the office floor and office air handler

Office Load Floor Summary					
Space Sensible	219,813	[BTUh]	Space Heating	51	[MBH]
Space Latent	19,928	[BTUh]	Fresh Air	3,775	[CFM]
Typical Office AHU Load (Serves 5 Floors)					
Space Sensible	1,099,065	[BTUh]	Space Heating	255	[MBH]
Space Latent	99,638	[BTUh]	Fresh Air	18,877	[CFM]

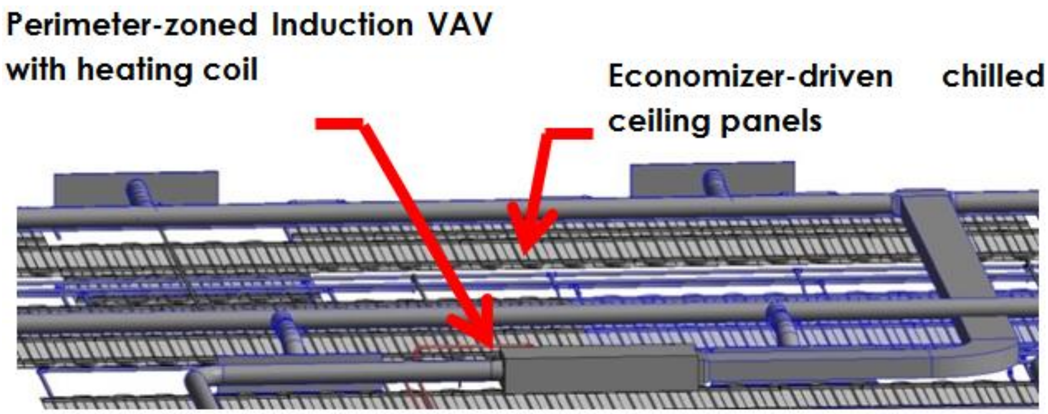


Figure 16. Picture illustrating the terminal equipment for the simultaneous heating and cooling scheme

HVAC Systems

On each office floor, a 100% Outside Air Unit provides fresh air to occupants while mitigating latent loads. Demand-controlled ventilation air is supplied on a zone-by-zone basis by VAV Induction terminals which are controlled by zone-level CO2 sensors. Perimeter zone terminals have a hot water coil which provides heat in the winter. Chilled ceiling panels mitigate sensible cooling loads and are directly supplied by cooling towers on the roof.

Cooling Season

Because of large sensible loads generated by solar gain, people, computers and the lighting system, an energy efficient cooling strategy was desired in order to mitigate these loads. Chilled ceiling panels were designed in order to be able to deliver both radiative and convective cooling. This option was chosen over a thermally-active chilled slab for the following reasons:

- Chilled slabs are approximately 25x heavier than radiant ceiling panels, introducing unwanted lateral forces into the structure during a design-level earthquake
- Because chilled ceilings are suspended above a space, they can take better advantage of convective heat transfer, affording chilled ceilings 1.7x greater heat flux
- Quality assurance during construction is easier to guarantee because the cooling system isn't embedded in concrete

A radiant cooling system was desired for 350 Mission because of its ability to take advantage of water-side economizer-driven free cooling for San Francisco's cooling season. Extensive cooling tower, plate-and-frame heat exchanger and chilled panel design was used to optimize chilled water ΔT, panel coverage, and cooling tower design conditions in order to allow the system to meet the design-level sensible cooling load, as well as perform at full capacity at 1% Design-day conditions.

On the 20th floor, it was determined that an **87% chilled ceiling coverage** was required in the open office in order to meet the peak cooling load. Though this is higher than typical coverage values, this panel density is a result of designing to **year-round water-side economizer use**. By designing to this condition, the **annual electricity required for radiant panel cooling is reduced by 57%** compared to serving the radiant panels with a centrifugal chiller. Panel design conditions for the 1% Cooling Condition are described in Table 8. It should also be noted that, due to potential acoustical concerns regarding large reflective surfaces, analysis was performed in order to ensure that speech intelligibility would not be negatively affected—an average reverberation time of **0.55** was found in the **250 – 4000 Hz** range, which is below the recommended **0.60 seconds**.

Table 9. Table illustrating the chilled ceiling design parameters

Chilled Ceiling Cooling Parameters			
V_{design}	1.0 gpm	ΔT	3.4 F
$T_{CHW,in}$	67.0 F	$T_{avg,surface}$	69.0 F
$T_{CHW,out}$	70.4 F	$Flux_{Cooling}$	16.2 BTUh/SF

Utilizing radiant cooling allows the sensible and latent loads to be decoupled, which, in an office environment in which sensible and latent loads can be fairly non-coincident, presents an advantage. A 100% Outdoor Air System was designed for the office levels. Each AHU serves five floors and has a variable-speed fan supply fan. Several dehumidification strategies were investigated including desiccant dehumidification, run-around coils and wrap-around coils. Run-around coils were decided on for the dehumidification technology because they reduced cooling coil size compared to using desiccant dehumidification. Run-around coils presented an advantage over wrap-around coils because run-around coils allowed the air to be supplied at a cold condition, whereas wrap-around coils return air to a neutral condition. By supplying fresh air at 50^{F}, mixed to 55^{F} at terminal units, instead of 62^{F}, the added cooling capacity of not rejecting heat back into the airstream presented an advantage over wrap-around coils. By supplying air at a colder condition, the overall cooling tower flow rate is reduced by **550 gpm and 500 chilled ceiling panels are avoided throughout the building, saving $100,000 of capital cost**, assuming roughly $200 per panel.

Heating Season

For the colder months of the year, both heating and cooling loads are present. Heat-producing people and equipment present in the core outweigh heat loss, while the perimeter zones see heating loads throughout the morning and evening. This was solved by using the Induction VAV terminals in the core zone to utilize economizer hours, mixing to 55F in the event of lower temperatures. Heating is then isolated to perimeter zones and coolth is not wasted by heating the entire airstream at the AHU.

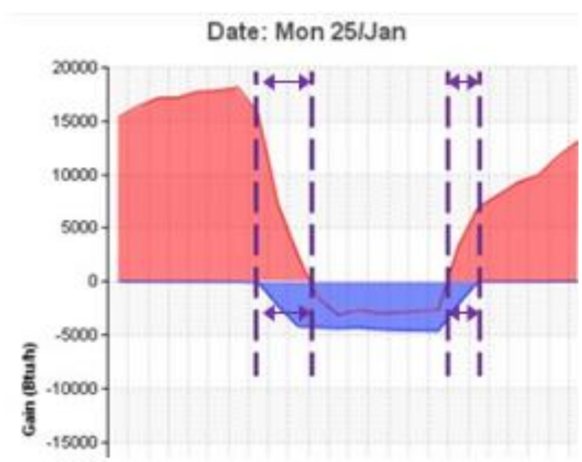


Figure 17. Daily profile showing the need for simultaneous heating and cooling

Plumbing Systems

The plumbing system for 350 Mission is directly integrated into the central plant and other key functions of the building as a whole. The non-potable demand will be served by the treated blackwater and greywater from the building, sewer and the rainwater tank on the roof. After solid separation occurs, the building wastewater is sent through the AquaCELL and is cleaned, then pumped to the parking garage, lobby, and the first 25 floors of the building. The rooftop rainwater tank will serve the top five floors of the system, with a bypass installed for the black water from the sewer to either service those floors or fill the rainwater tank if there is not enough rainwater to meet the demand of the top five floors.

Design for Resilience and Life Safety

The office floors of 350 Mission were designed with endurance in mind. Seismically bracing a chilled ceiling system is easier than ensuring seismic resilience for a comparable Underfloor Air system. The panels are also made of lightweight aluminum with copper piping, making them approximately 8x lighter than a UFAD system decreasing the lateral seismic loading experienced during an earthquake.

The fire protection system is an automated sprinkler system designed to activate appropriately when necessary. The system is designed to meet code and is sequenced into three different riser areas. The fire department connection from the street is diverted into main runs which service the parking garage, floors 1-16, and floors 17-30. Each floor has a dedicated sprinkler layout that is serviced from standpipes located in the two stairwells located within the core. Calculations were done to determine the necessary GPM and pressure that each pump must be designed to reach the farthest sprinkler on each floor.

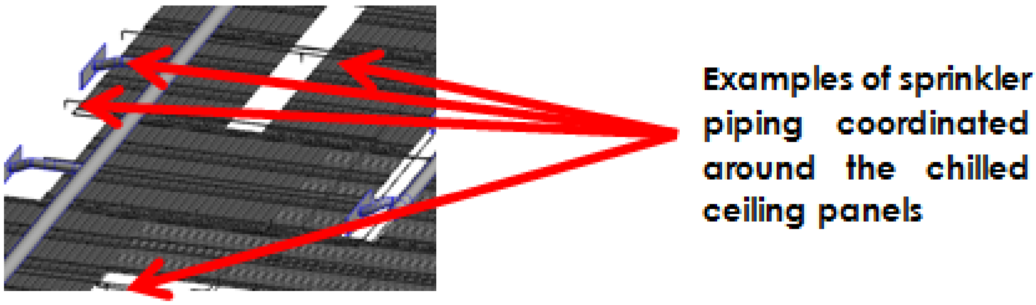


Figure 18. Picture illustrating the coordination of MEP trades

The airside system was designed based on the airflow design method. When a fire occurs on a specific floor, that floor is isolated from the others and the air handling unit responsible for that floor will exhaust the smoke through the return duct system and expel it outdoors via a diverting damper. To accompany the smoke evacuation system, a separate riser will supply air to the stairwells to provide a **positive pressurization of 0.15 in wg** to allow occupants to evacuate into the stairwell while simultaneously preventing the smoke from entering the space.

8.2 Efficient Plant

In order to ensure that 350 Mission met its Near-net Zero Goals, the heating and cooling plant of the building was optimized in order to require minimal input to deliver heating and cooling throughout the year. The details of each plant are discussed below:

8.2.1 Cooling Plant

The cooling plant was designed to serve diverse end-uses throughout the building. In order to maximize the efficiency of the cooling system, the cooling plant was divided into High Temperature Chilled Water (HCHW) and Low Temperature Chilled Water (LCHW). In order to generate HCHW and LCHW, a cooling tower system and an absorption cooling system was designed to deliver each commodity to the main spaces within the building, respectively. A water-to-water heat pump is designed to serve the Restaurant.

Cooling Tower HCHW System

San Francisco's climate can be characterized by hot/dry and mild/humid and during the ASHRAE 1% Cooling Design Day, the coincident ambient wet-bulb is only 62^F. Because of this climatic characteristic and the fact that chilled ceiling systems can leverage large cooling capacities at high CHW supply temperatures, **(4) Cooling Towers** were designed to supply HCHW to the building's radiant conditioning systems at a set-point of 67^F. Through using cooling towers with VFD fans, the cooling energy required to maintain an adequate set-point is reduced dramatically as the ambient wet-bulb temperature decreases.

Table 10. Table illustrating the design conditions of the cooling towers

Cooling Tower Loading Summary					
Flow per Cell	980	*[gpm]*	T_{in}	68	*[F]*
Number of Cells	4	*[#]*	T_{out}	65	*[F]*

In order to **avoid fouling** throughout the building's radiant panels, a **plate-and-frame heat exchanger** (PFHX) was designed to transfer heat from the cooling tower chilled water to the building's chilled water loop. This roof-mounted PFHX also presented the advantage of isolating the gravity head to height of the cooling tower, instead of the height of the building. This approach was introduced to minimize pumping energy. The cooling tower design conditions are outlined in Table 10.

This cooling strategy was modeled as a Strainer Cycle in IES Virtual Environment in order to compare against a centrifugal chiller. Simulations showed that, despite higher pumping energy due to increased flow rates, the lack of a compressor enabled **savings of 57% over supplying the chilled ceilings and thermal slab with an equivalent centrifugal chiller.**

The acoustics of having four large cooling towers on the roof was also modeled in order to ensure that there were no negative effects on surrounding buildings. The A-weighted sound pressure level 40 feet horizontal from the roof is calculated to be 32 dBA due to the attenuation from the roof parapet.

Absorption Chiller LCHW System

Because office buildings contain large numbers of people, large latent loads are present during operating hours. An **85-ton single-effect absorption chiller** was designed to generate 44^F chilled water using the low-grade exhaust and jacket heat from the IC Engine. Double-effect alternatives were explored; however the heat quality was not sufficient to drive the generator of a sufficiently-sized chiller.

Table 11. Table illustrating the design conditions for the absorption chiller

Absorption Chiller Loading Summary					
Coincident Coil Loads	81.9	[tons]	T_{CHWR}	54	[F]
Flow Rate$_{LCHW}$	197	[gpm]	T_{CHWS}	44	[F]

On the office floors, a run-around coil brings the on-coil temperature to saturation, rejecting heat into the exhaust air stream. The absorption chiller then cools air down to 50^F and 51.3 Gr/lb, which is mixed at the Induction VAV terminal to 55^F. This handles the design latent load of 19,930 BTUh per office floor. This utilization of CHP waste heat, coupled with maintaining high digester temperatures, ensures a large heat-to-power ratio (λ_D) which maximizes the efficiency and economic viability of combined heat and power.

The absorption chiller uses the solid-separated wastewater from the BioMethane plant as a heat rejection loop before it is re-injected into the municipal sewer. Using wastewater as a heat rejection loop is becoming increasingly popular in Philadelphia and a packaged system by NovaThermal Energy is making its application easier to adopt. For the application in 350 Mission, however this heat rejection method makes even more economic sense because sewer water has already been scalped and filtered by another process in the building—the resource is already present in high volumes. By using solid-separated wastewater as a heat sink, this shares auxiliary energy across multiple end-uses, increasing the overall system efficiency. It should also be noted that San Francisco limits sewer discharge temperatures to 125^F. The chiller's cooling water exit temperature does not exceed 98^F during operation, so after mixing it cannot exceed the limit.

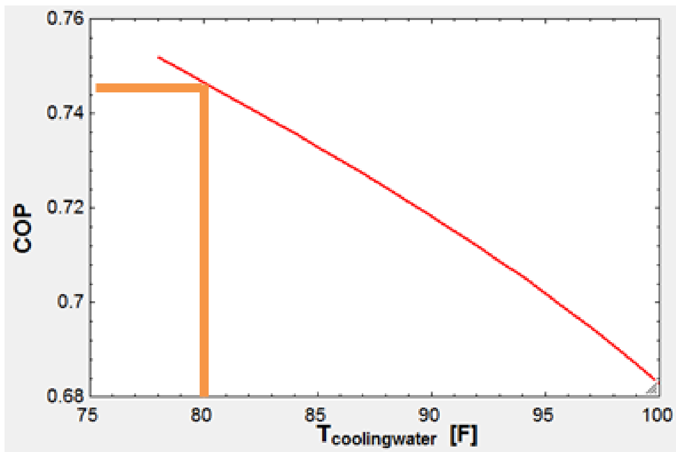


Figure 19. Graph illustrating COP vs. cooling water inlet temperature for a generator inlet temperature of 200F

In order to maximize the efficiency of the absorption chiller beyond the rated conditions, a generator water temperature of 200^F and a cooling water temperature of 80^F was selected in order to **raise the COP from 0.68 to 0.75**. The condenser water temperature is selected with a 10F safety margin above the lower limit of 70^F in order to avoid LiBr crystallization.

Water-to-Wastewater Heat Pump

A dedicated **20-ton water-to-wastewater heat pump** is used to provide chilled water to the restaurant's dedicated AHU. It was desired that this system be separate from the rest of the building due to the varying requirements and schedules of restaurant tenants. A dedicated system allows maximum tenant flexibility. The heat pump produces 44^F LCHW and rejects heat to the solid-separated wastewater which is not directed to the AquaCELL blackwater reclamation system.

Table 12. Table illustrating heat pump design conditions

Wastewater Heat Pump Loading Summary					
Coincident Coil Loads	18.2	[tons]	T_{CHWR}	54	[F]
Flow Rate$_{LCHW}$	44	[gpm]	T_{CHWS}	44	[F]

8.2.2 Heating Plant

The IC Engine which is used to generate electricity for 350 Mission also produces a constant stream of jacket and exhaust heat at a rate of **785** and **570 MBH**, respectively. This is sufficient to meet 91% of heating loads throughout the year, however for 9% of the year a supplemental boiler is required to meet perimeter heating loads. A **2,500 MBH boiler** is designed in order to generate hot water for perimeter heating coils.

Chapter 9

Conclusion

The design for 350 Mission was driven by the desire to leverage advanced design tools to create a building which engages with the surrounding urban ecology to enable **Near-net Zero Energy, Water, Waste and Emissions** while creating a quality indoor environment for occupants. BIM allowed for the creation of efficient distribution networks, reducing energy consumption while analytical modeling software enabled the optimization of the holistic energy performance of the building. At the end of the design process, ***350 Mission achieved its Near-net Zero goals***:

ENERGY	WATER	WASTE	EMISSIONS
EUI: -0.02	GAL: 1,169,158	TONS: 321	$TONS_{CO2}$: 25
100% REDUCTION	84% REDUCTION	95% REDUCTION	99% REDUCTION

It was only through careful analysis, and continuous interdisciplinary collaboration, that the proposed solution was possible. Through cross-disciplinary, integrated design decisions, the basement structure and foundation was able to be modified in order to create space for the **BioMethane Plant** and **AquaCELL**. This **allowed large quantities of thermal and electric energy to be created**, shaping the design of the **heating** and **absorption cooling system**. It was also through interdisciplinary collaboration that an **optimized façade** which enhanced construction, structural, electrical and thermal performance, reduced space heat gains such that a **completely compressor-less space cooling system** was possible for 350 Mission.

Through all of these decisions, 350 Mission exists as an **environmentally-beneficial structure**—the building absorbs and treats waste streams in order to **produce 2,715,600 kWh** and **119,000 therms** on-site per year while **recycling 1,680,000 gallons of water** on-site. 350 Mission saves over **52,830 tons of CO_2, 85,148,815 kWh, 4,463,600 therms, 296,333,500 gallons of potable water** and **25,500 tons of landfill waste** over its **50-year lifecycle**. Through interacting with the community of San Francisco, 350 Mission is able to be designed not only as an architectural landmark, but as a *precedent-setting example of holistic sustainability*.

Appendix A

Loads and Heating/Cooling Plant

Typical Office Floors

Zone Name	Cooling Season								Heating Season					
	DOAS		Space Conditions				Chilled Ceiling		DOAS			Space Conditions		Terminal Unit
	Outside Air	Cooling Coil Load Contribution	Peak Latent Load	Peak Sensible Load	Supply Air Latent Capacity	Supply Air Sensible Capacity	Sensible Load	Number of Panels	Outside Air	Supplemental Induced Heating Airflow	Total Terminal Unit Flow	Peak Sensible Heating Load	Coincident Supply Air Sensible Cooling Capacity	HTW Coil Load
	[CFM]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[#]	[CFM]	[CFM]	[CFM]	[BTUh]	[BTUh]	[BTUh]
Office Perim. West	486	10,719	4,960	39,883	8,541	14,175	25,708	33	486	119	605	17,648	-	35,949
Office Core West	257	5,660	4,495	14,662	4,510	7,485	7,177	9	257	-	257	-	7,485	-
Corridor West	40	891	-	1,234	710	1,178	56	-	40	-	40	-	1,178	-
Office Perim. South	486	10,719	4,960	46,216	8,541	14,175	32,041	36	486	83	569	16,600	-	33,815
Office Core South	257	5,660	4,495	12,541	4,510	7,485	5,057	6	257	-	257	-	7,485	-
Corridor South	40	891	-	1,237	710	1,178	59	-	40	-	40	-	1,178	-
Meeting Area 1	355	7,837	4,030	15,573	6,244	10,364	5,209	6	355	-	355	-	10,364	-
Meeting Area 2	99	2,181	1,550	10,574	1,738	2,885	7,689	9	99	-	99	-	2,885	-
Meeting Area 3	136	3,002	1,705	10,965	2,392	3,970	6,994	9	136	-	136	-	3,970	-
Corridor Central	47	1,032	-	4,370	822	1,365	3,005	4	47	-	47	-	1,365	-
Lounge Perimeter	362	7,992	3,615	22,039	6,368	10,570	11,469	13	362	-	362	10,405	-	21,531
Lounge Core	133	2,933	2,143	12,256	2,337	3,878	8,378	11	133	-	133	-	3,878	-
Pantry	60	1,326	969	2,048	1,056	1,753	295	-	60	-	60	-	1,753	-
Lobby	621	13,690	10,950	14,497	10,908	18,104	-	-	621	-	621	-	18,104	-
Misc. Room	263	5,793	4,379	12,712	4,616	7,661	5,051	6	263	-	263	1,909	-	15,606
Stairwell East	28	628	-	-	500	830	-	-	28	-	28	-	830	-
Stairwell West	28	628	-	-	500	830	-	-	28	-	28	-	830	-
Restrooms	36	791	-	8,633	630	1,046	7,587	10	36	-	36	-	1,046	-
Server Room	4	86	-	2,000	69	114	1,886	2	4	-	4	-	114	-
Fan Room	36	791	-	7,548	630	1,046	6,502	8	36	123	159	4,628	-	9,427
Coincident Peak Totals:	1,559	34,382	19,928	219,813	27,395	45,468	174,345	164			3,898	51,190	25,798	116,328

Upper and Lower Lobby

Zone Name	Cooling Season								Heating Season				
	DOAS		Space Conditions				Thermal Slab		DOAS		Space Conditions	Supplemental Heat	Thermal Slab
	Outside Air	Cooling Coil Load Contribution	Peak Latent Load	Peak Sensible Load	Supply Air Latent Capacity	Supply Air Sensible Capacity	Sensible Load	Slab Capacity Needed	Outside Air	Heating Coil Load	Peak Sensible Heating Load	Coincident Supply Air Sensible Cooling Capacity	Slab Capcacity Needed
	[CFM]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[BTUh/SF]	[CFM]	[BTUh]	[BTUh]	[BTUh]	[BTUh/SF]
Open Lobby Entry	7,398	133,158	130,470	271,640	129,971	215,715	55,925	13	7,398	223,705	107,146	-	25
Retail East	1,193	21,475	1,866	43,807	20,961	34,790	9,017	14	1,193	36,079	22,530	-	36
Retail West	112	2,024	1,116	2,953	1,975	3,279	-	-	112	3,400	3,130	-	8
Fire Command Room	16	285	-	-	278	462	-	-	16	479	-	-	-
Gas Meter Room	6	110	-	-	107	177	-	-	6	184	-	-	-
Elevator Lobby	675	12,155	11,910	14,051	11,864	19,692	-	-	675	20,421	4,060	-	10
Public Restroom	980	17,640	-	30,615	17,218	28,577	2,038	14	980	29,635	17,582	12,200	36
Exit Passageway	31	551	-	843	538	893	-	-	31	926	6,304	-	20
Upper Lobby	3,687	66,364	59,370	136,037	64,775	107,509	28,528	14	3,687	111,491	36,433	-	18
Stairwell East	50	899	-	-	877	1,456	-	-	50	1,510	-	-	-
Stairwell West	50	899	-	-	877	1,456	-	-	50	1,510	-	-	-
Coincident Peak Totals:	14,198	255,559	204,732	499,946	249,443	414,005	95,507		14,198	429,339	197,185	12,200	

Restaurant

Zone Name	Cooling Season						Heating Season		
	DOAS		Space Conditions				DOAS		Space Conditions
	Outside Air	Cooling Coil Load Contribution	Peak Latent Load	Peak Sensible Load	Supply Air Latent Capacity	Supply Air Sensible Capacity	Outside Air	Heating Coil Load	Peak Sensible Heating Load
	[CFM]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[BTUh]	[CFM]	[BTUh]	[BTUh]
Dining Area	4,717	84,899	35,422	126,762	46,570	127,349	4,717	280,167	64,278
Kitchen	2,082	37,467	20,595	36,822	20,552	56,201	2,082	123,642	15,159
Men's Restroom	5	98	-	2,453	54	147	5	165	-
Women's Restroom	5	98	-	2,461	54	147	5	165	-
Corridor	53	952	-	935	522	1,428	53	1,599	-
Coincident Peak Totals:	6,862	123,515	56,017	169,433	67,752	185,272	6,862	405,739	79,437

Absorption Chiller Schedule

Name	Location	Chilled Water				Cooling Water				Generator Water			
		Flow Rate	T_{CHWS}	T_{CHWR}	$Q_{evaporator}$	Flow Rate	T_{CWS}	T_{CWR}	$Q_{cooling}$	Flow Rate	T_{HWS}	T_{HWR}	$Q_{generator}$
		[gpm]	[F]	[F]	[BTUh]	[gpm]	[F]	[F]	[BTUh]	[gpm]	[F]	[F]	[BTUh]
ACH - 1	B4 - Basement	197	44	54	(982,800)	374	80	92	2,244,000	87	200	170	(1,310,000)

Supplemental Boiler Schedule

Name	Location	Heat Output				Fuel Input	
		Water Flow Rate	T_{HWS}	T_{HWR}	Q_{boiler}	Flow Rate	LHV
		[gpm]	[F]	[F]	[BTUh]	[CFM]	[BTU/ft^3]
SB - 1	B4 - Basement	148	160	130	2,220,000	521	80

Wastewater Heat Pump Schedule

Name	Location	Power Consumption	Chilled Water				Condenser Water			
			Flow Rate	T_{CHWS}	T_{CHWR}	$Q_{evaporator}$	Flow Rate	T_{CWS}	T_{CWR}	$Q_{cooling}$
		[kW]	[gpm]	[F]	[F]	[BTUh]	[gpm]	[F]	[F]	[BTUh]
HP - 1	3rd Floor Mech Room	14	47	44	54	(236,600)	50	80	91	282,500

Appendix B

BioMethane Plant

Municipal Food Waste Rate		Organic Sludge Mass Flow	
8,500	[gpd]	113.4	[g/s]
Building Food Waste Rate		**Organic Sludge Volume Flow**	
52	[gpd]	0.11	[L/s]
Building Sewage Rate		**Sewage Solids Accumulation**	
300	[gpd]	2,863	[gpd]
Wastewater Flow Rate		**CH4 Mass Branching Ratio**	
1,500	[gpm]	0.35	[m3 CH4/kg]
VOS Concentration		**COD of Mixed Food Waste**	
300	[mg/L]	252,000	[mg/L]
VOS Mass Flow		**COD of Human Feces**	
28.4	[g/s]	37,211	[mg/L]

Methane Generation Process

Hydrolysis: carbohydrates, fats and proteins are converted to sugars, fatty acids and amino acids, respectively

Acidogenesis: hydrolysis byproducts are transformed into carbonic acids, alcohols, hydrogen, carbon dioxide and ammonia

Aceteogenesis: byproducts of acidogenesis are converted to hydrogen, acetic acid and carbon dioxide

Methanogenesis: aceteogenesis byproducts are converted to methane and carbon dioxide

Production Model Variables

Q_{CH4}: Methane production

Q_w: Influent flow rate

S_{t0}: Original concentration of volatile solids

S_{te}: Final concentration of volatile solids

M: Mass branching ratio

$\eta_{digestion}$: Digestion efficiency

S': Normalized solids concentration

k: Reaction constant

n: Reaction order

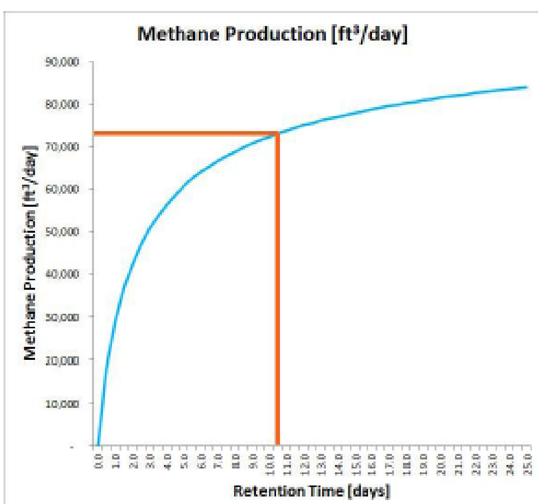
t: Standardized retention time

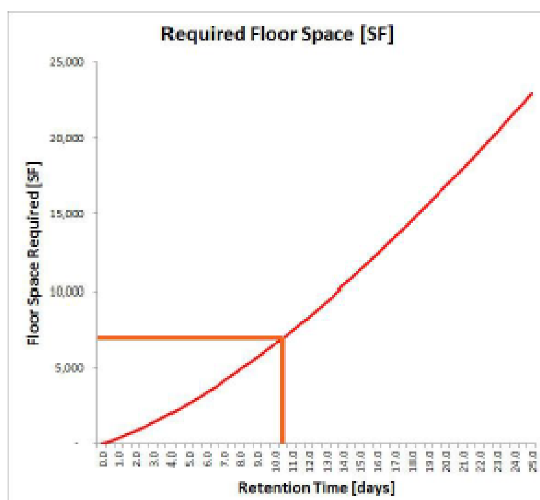
X_v/X_w: Average mixed concentration

Retention Time [days]	Avg. Norm. Conc. [--]	Digestion Efficiency [%]	Methane Production [ft3/day]	Biogas Production [ft3/day]		Tank Volume [gal]	Tank Volume [ft3]	Number of Tanks [#]	Required Space [SF]
0.0	1.000	0%	-	-		-	-	-	-
0.5	0.908	17%	17,925	27,577		6,289	841	4	89
1.0	0.841	27%	29,032	44,665		13,569	1,814	9	191

(...etc...)

8.0	0.518	65%	68,883	105,974		176,233	23,559	123	2,485
8.5	0.508	66%	69,859	107,475		191,001	25,533	133	2,693
9.0	0.498	67%	70,761	108,863		206,109	27,553	144	2,906
9.5	0.489	68%	71,599	110,152		221,547	29,617	154	3,124
10.0	0.481	68%	72,379	111,352		237,307	31,723	165	3,346
10.5	0.473	69%	73,109	112,475		253,381	33,872	176	3,572





BioMethane Production Model *(Procedure from Slovenian National Inst. Of Chemistry)*

Step 1: Define needed equation to find methane volume

$$Q_{CH_4} = Q_w(S_{T0} - S_{Te})M \Longrightarrow Q_{CH_4} = (\eta_{digestion})Q_w M S_{T0}$$

Step 2: Define digestion efficiency based on normalized VSS concentration per particulate influent

$$\eta_{digestion} = \frac{(S_{T0} - S_{Te})}{S_{T0}} = \frac{(S'(t=0) - S'(t))}{S'(t=0)} = \frac{(1 - S')}{1}$$

Step 3: Normalize VSS concentration

$$S' = \frac{S}{S_0}$$

Step 4: Model VSS decay rate as a function of kinetic reaction order $(n = 3)$ and reaction constant (k)

$$\frac{\partial S'}{\partial t} = -k \cdot (S')^n$$

Step 5: Define normalized concentration based on remaining VSS per particulate influent; Thermophilic digestion constants are defined as $(k' = 0.449)$ and $(c_1 = 1)$

$$S' = \frac{1}{\sqrt{c_1 + 2k' \cdot t}}$$

Step 6: Define standard residence time based on digester flow, volume and average remaining VSS concentration

$$t = \frac{VX_v}{Q_w X_w}$$

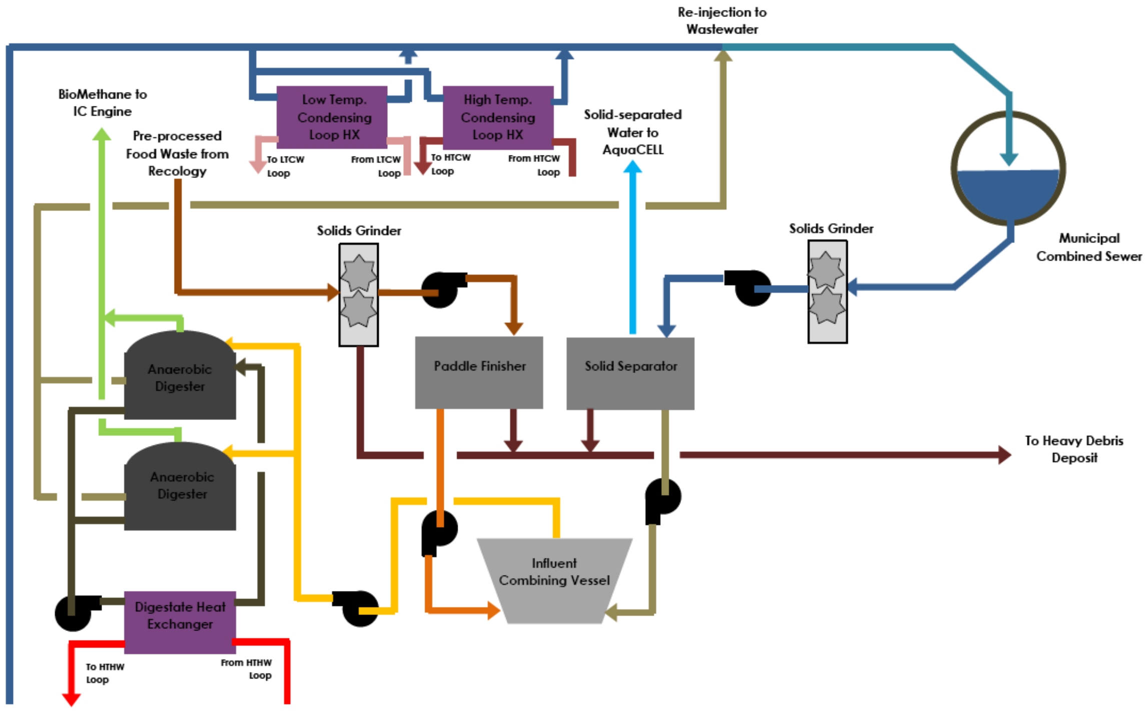
Step 7: Define average remaining VSS concentration

$$\left(\frac{X_v}{X_w}\right) = \frac{1}{t}\int_0^t \frac{1}{\sqrt{c_1 + 2k' \cdot t}}$$

Step 8: Combine terms to find methane production based on tank volume, standard residence time, influent mass branching ratio and influent Chemical Oxygen Demand

$$Q_{CH_4} = \left(\frac{V}{t^2}\int_0^t \frac{1}{\sqrt{c_1 + 2k' \cdot t}}\right)\left(1 - \frac{1}{\sqrt{c_1 + 2k' \cdot t}}\right) MS_{T0}$$

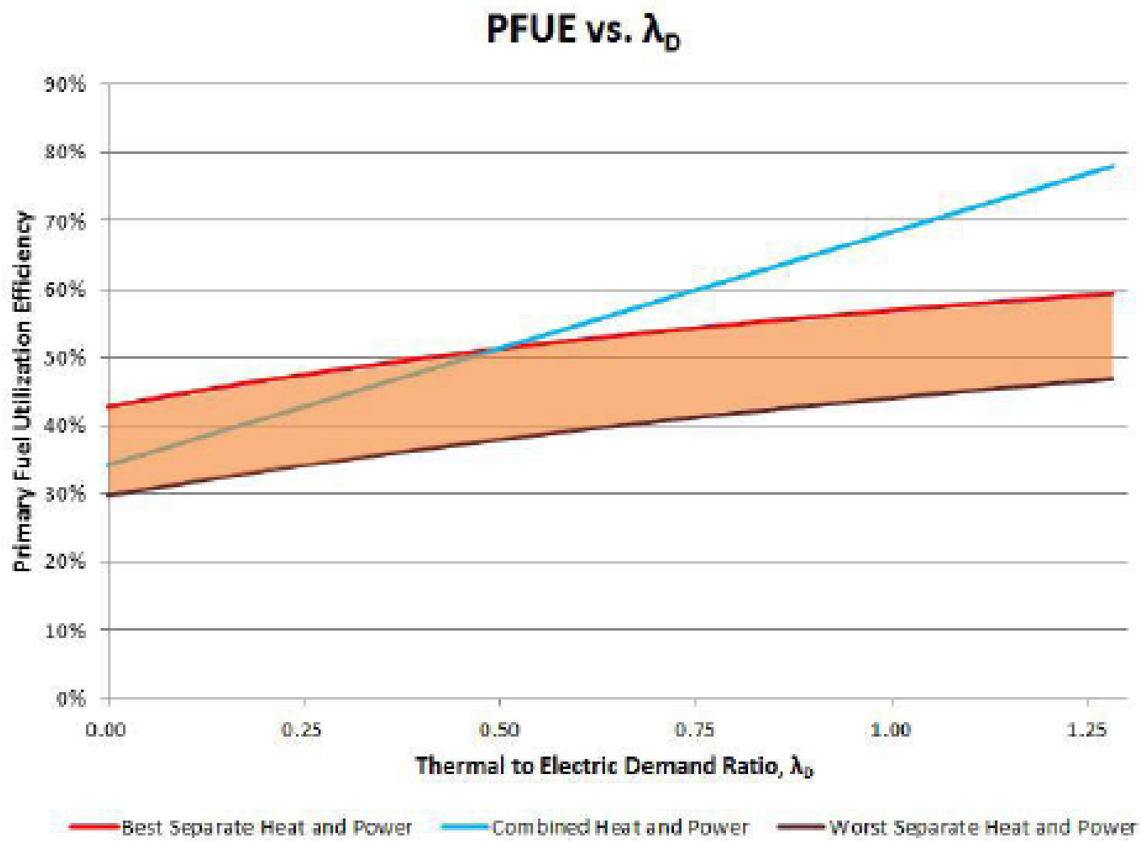
Step 9: Set spatial constraints and analyze influent characteristics and quantities

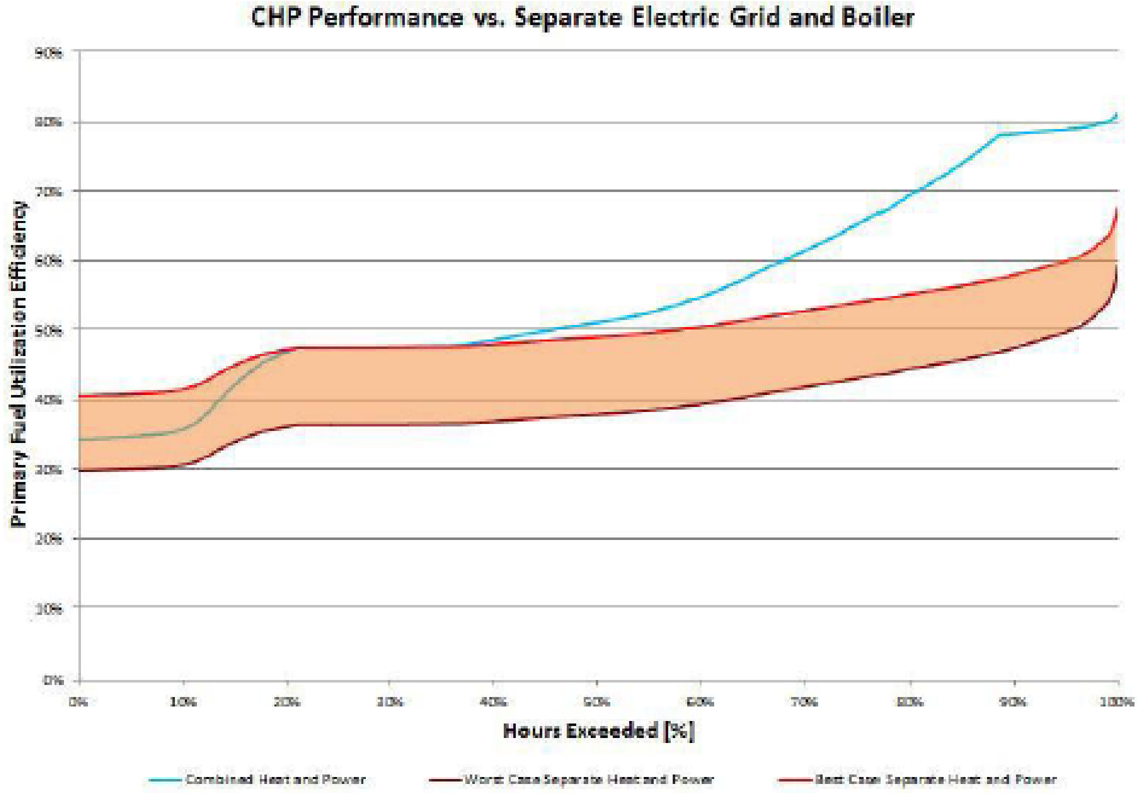

Re-injection to Wastewater
BioMethane to IC Engine
Low Temp. Condensing Loop HX
High Temp. Condensing Loop HX
To LTCW Loop
From LTCW Loop
To HTCW Loop
From HTCW Loop
Solid-separated Water to AquaCELL
Pre-processed Food Waste from Recology
Solids Grinder
Solids Grinder
Municipal Combined Sewer
Anaerobic Digester
Anaerobic Digester
Paddle Finisher
Solid Separator
To Heavy Debris Deposit
Influent Combining Vessel
Digestate Heat Exchanger
To HTHW Loop
From HTHW Loop

Appendix C

CHP Calculations

Waukesha IC Engine		
Biomethane Flow Rate	4,649	[ft³/hr]
Usable Electricity	310	[kW]
Usable Jacket Heat	785	[kBTUh]
Exhaust Heat Output	877	[kBTUh]
HX Effectiveness	65%	
Usable Exhaust Heat	570	[kBTUh]
Electrical Efficiency	34.2%	
Overall Efficiency	78.0%	



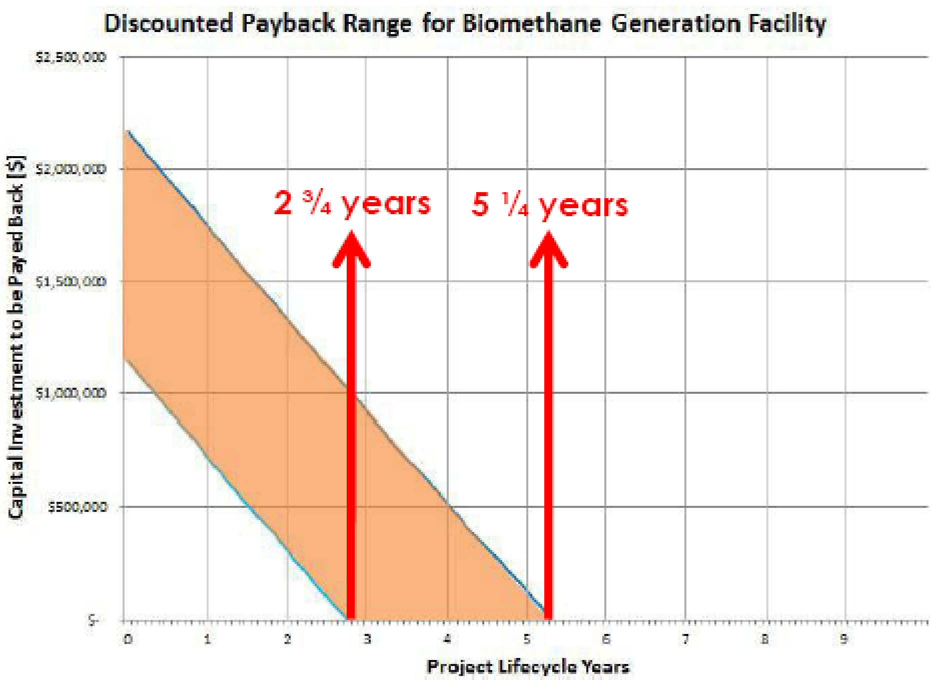


$$PFUE_{CHP} = \frac{\dot{q}_d + \dot{e}^-{}_d}{\dot{q}_{fuel} + \begin{cases} \left(\frac{\dot{q}_d - \dot{q}_{cap}}{\eta_b}\right) \; if \;\; \dot{q}_d > \dot{q}_{cap} \\ 0 \; if \; \dot{q}_d \leq \dot{q}_{cap} \end{cases} + \begin{cases} \left(\frac{\dot{e}^-{}_d - \dot{e}^-{}_{cap}}{\eta_{gen} \cdot \eta_{trans,dist}}\right) \; if \;\; \dot{e}^-{}_d > \dot{e}^-{}_{cap} \\ 0 \; if \; \dot{q}_d \leq \dot{q}_{cap} \end{cases}}$$

$$PFUE_{SHP} = \frac{\dot{q}_d + \dot{e}^-{}_d}{\left(\frac{\dot{q}_d}{\eta_b}\right) + \left(\frac{\dot{e}^-{}_d}{\eta_{gen} \cdot \eta_{trans,dist}}\right)}$$

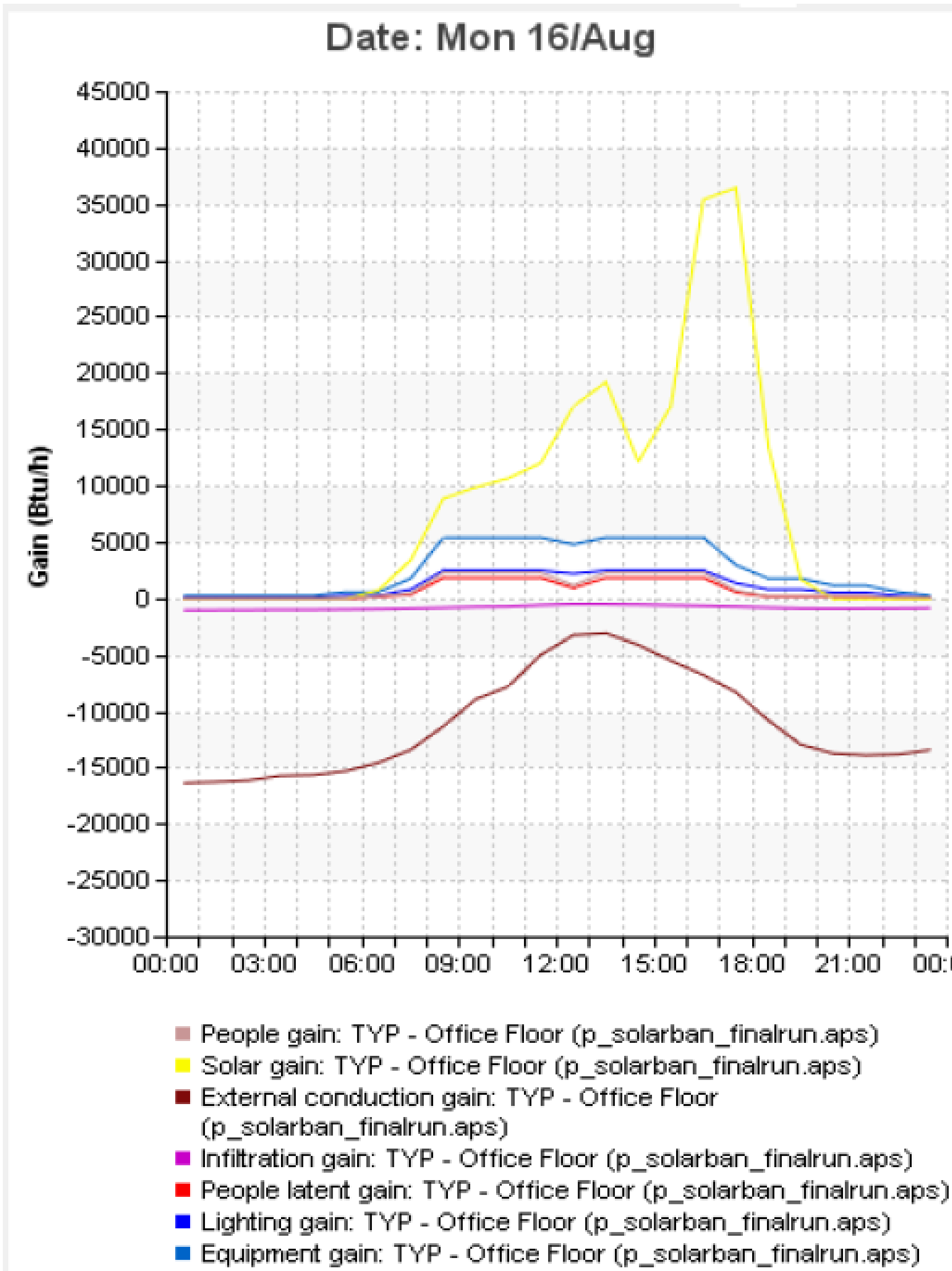
Appendix D

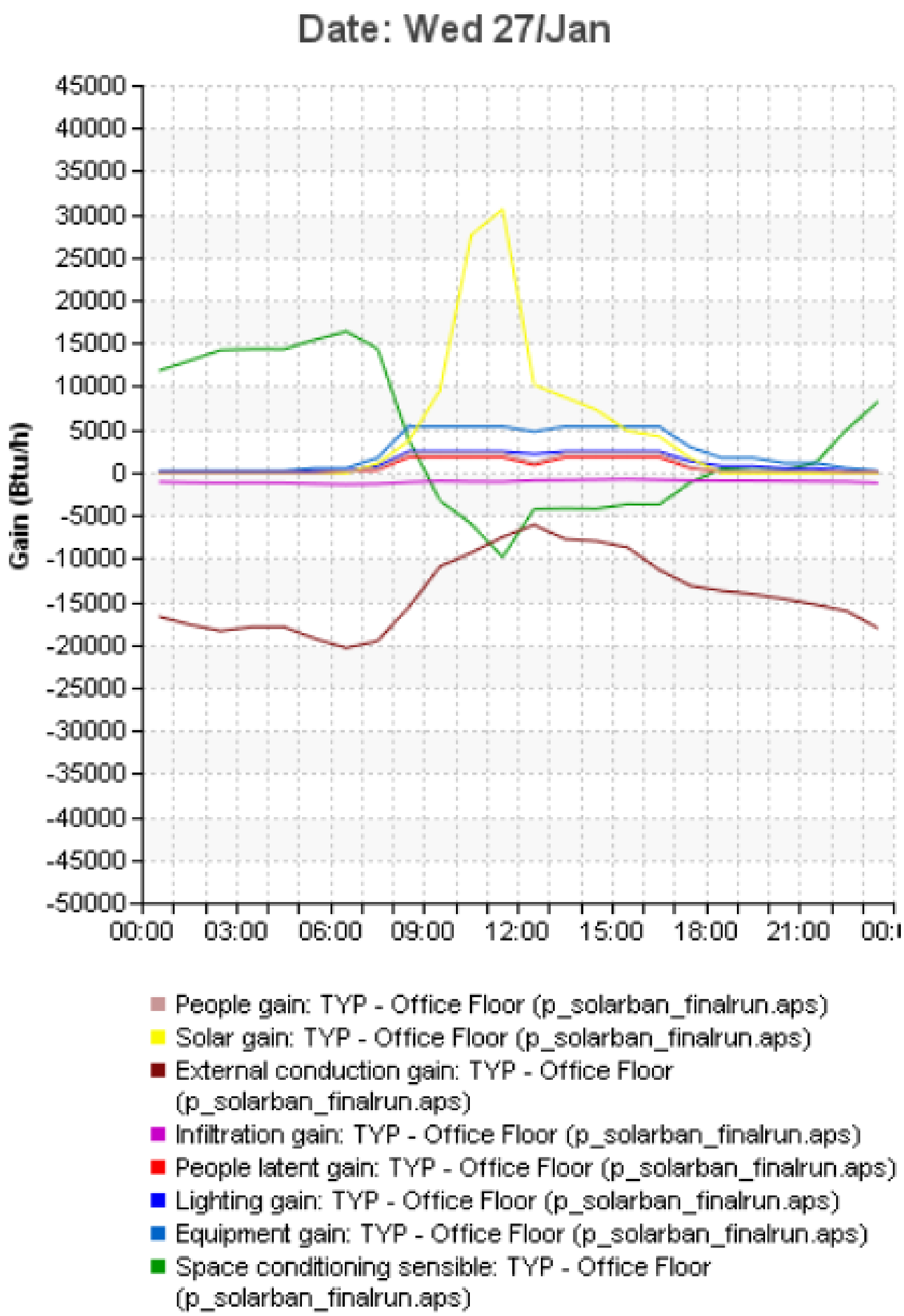
Life Cycle Economics

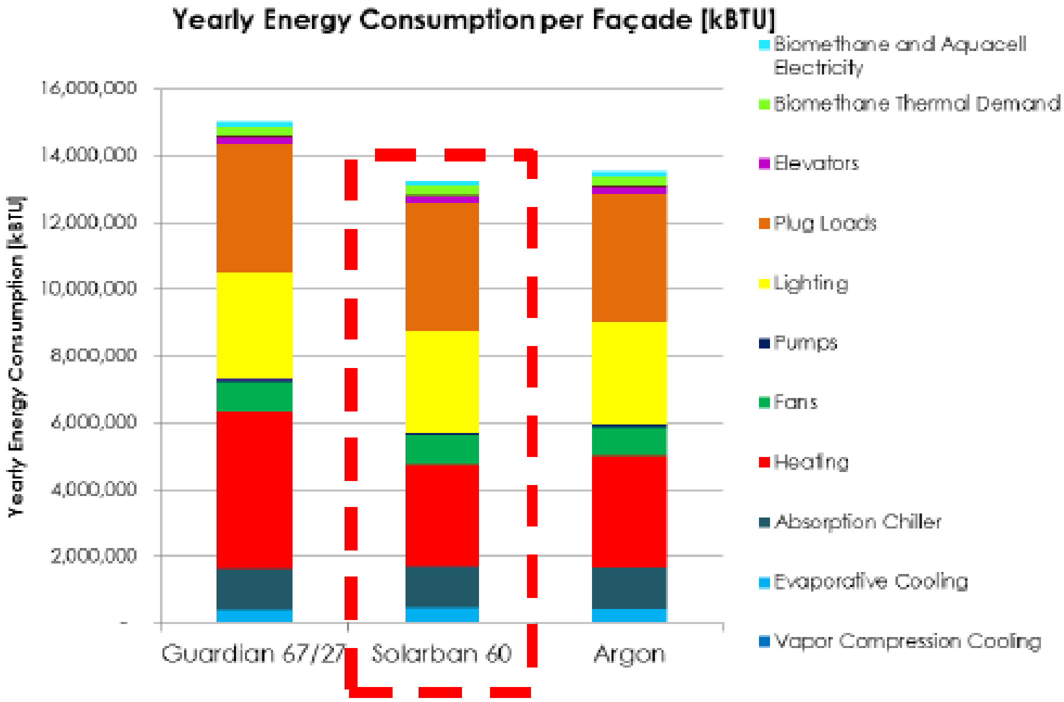


Appendix E

Passive Façade Heat Flux Study

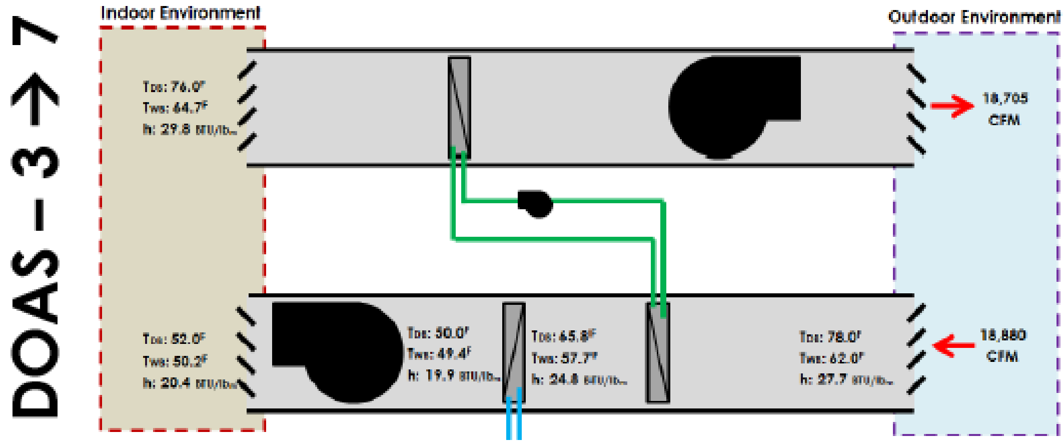


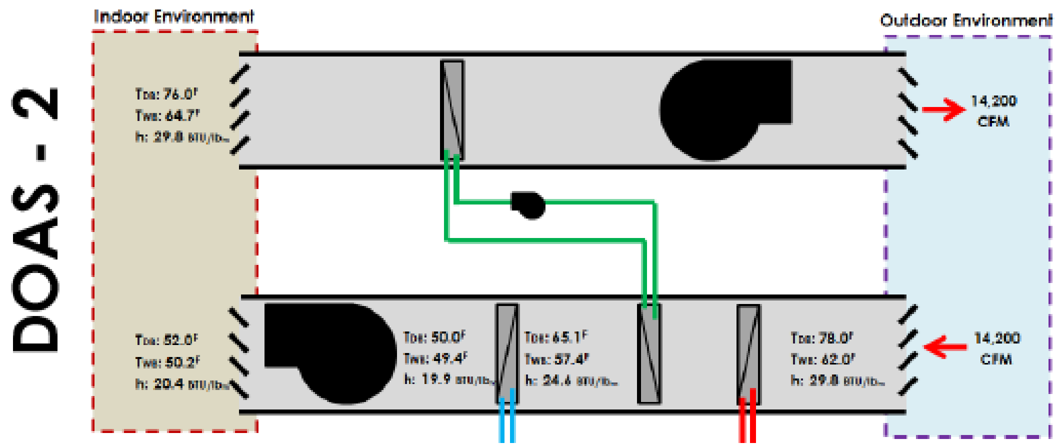

Date: Wed 27/Jan
Gain (Btu/h)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
People gain: TYP - Office Floor (p_solarban_finalrun.aps)
Solar gain: TYP - Office Floor (p_solarban_finalrun.aps)
External conduction gain: TYP - Office Floor (p_solarban_finalrun.aps)
Infiltration gain: TYP - Office Floor (p_solarban_finalrun.aps)
People latent gain: TYP - Office Floor (p_solarban_finalrun.aps)
Lighting gain: TYP - Office Floor (p_solarban_finalrun.aps)
Equipment gain: TYP - Office Floor (p_solarban_finalrun.aps)
Space conditioning sensible: TYP - Office Floor (p_solarban_finalrun.aps)

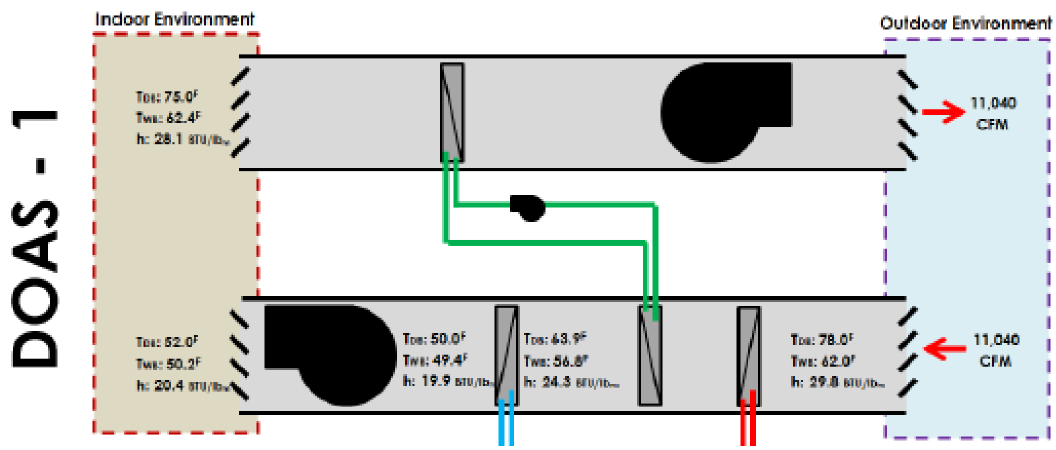

Yearly Energy Consumption per Façade [kBTU]
Yearly Energy Consumption [kBTU]
16,000,000
14,000,000
12,000,000
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
-
Guardian 67/27
Solarban 60
Argon
Biomethane and Aquacell Electricity
Biomethane Thermal Demand
Elevators
Plug Loads
Lighting
Pumps
Fans
Heating
Absorption Chiller
Evaporative Cooling
Vapor Compression Cooling

Appendix F

Air Handling Units







Appendix G

Ventilation and Exhaust

Ventilation Calculations

Office Floors 5 - 30

Zone Name	Zone Type	People [#]	Area [SF]	People OA Rate [CFM]	Area OA Rate [CFM]	Breathing Zone OA [CFM]	Ez [%]	Delivered OA [CFM]	Meets LEED 30% [Y/N]	Space Latent Load [BTUh]	Latent Load Handled [BTUh]	% Load Handled [%]	Sensible Capacity Added [BTUh]
Office Perim. West	Office	32	1,963	5.0	0.06	278	100%	486	Y	4,960	(8,541)	172%	14,175
Office Core West	Office	29	874	5.0	0.06	197	100%	257	Y	4,495	(4,510)	100%	7,485
Corridor West	Corridor	-	518	-	0.06	31	100%	40	Y	-	(710)		1,178
Office Perim. South	Office	32	1,963	5.0	0.06	278	100%	486	Y	4,960	(8,541)	172%	14,175
Office Core South	Office	29	874	5.0	0.06	197	100%	257	Y	4,495	(4,510)	100%	7,485
Corridor South	Corridor	-	518	-	0.06	31	100%	40	Y	-	(710)		1,178
Meeting Area 1	Meeting Room	26	654	5.0	0.06	169	100%	355	Y	4,030	(6,244)	155%	10,364
Meeting Area 2	Meeting Room	10	435	5.0	0.06	76	100%	99	Y	1,550	(1,738)	112%	2,885
Meeting Area 3	Meeting Room	11	829	5.0	0.06	105	100%	136	Y	1,705	(2,392)	140%	3,970
Corridor Central	Corridor	-	600	-	0.06	36	100%	47	Y	-	(822)		1,365
Lounge Perimeter	Lounge	23	933	5.0	0.06	173	100%	362	Y	3,615	(6,368)	176%	10,570
Lounge Core	Lounge	14	553	5.0	0.06	102	100%	133	Y	2,143	(2,337)	109%	3,878
Pantry	Lounge	6	250	5.0	0.06	46	100%	60	Y	969	(1,056)	109%	1,753
Lobby	Lobby	55	365	5.0	0.06	296	100%	621	Y	10,950	(10,908)	100%	18,104
Misc. Room	Meeting Room	28	565	5.0	0.06	175	100%	263	Y	4,379	(4,616)	105%	7,661
Stairwell East	Corridor	-	365	-	0.06	22	100%	28	Y	-	(500)		830
Stairwell West	Corridor	-	365	-	0.06	22	100%	28	Y	-	(500)		830
Restrooms	Restroom	-	460	-	0.06	28	100%	36	Y	-	(630)		1,046
Server Room	Electrical Room	-	50	-	0.06	3	100%	4	Y	-	(69)		114
Fan Room	Mechanical Room	-	460	-	0.06	28	100%	36	Y	-	(630)		1,046
Totals						2,293		3,775		48,251	(66,332)		110,092

Upper and Lower Lower Lobby

Zone Name	Zone Type	People [#]	Area [SF]	People OA Rate [CFM]	Area OA Rate [CFM]	Breathing Zone OA [CFM]	Ez [%]	Delivered OA [CFM]	Meets LEED 30% [Y/N]	Space Latent Load [BTUh]	Latent Load Handled [BTUh]	% Load Handled [%]	Sensible Capacity Added [BTUh]
Open Lobby Entry	Lobby	652	4,349	5.0	0.06	3,523	100%	7,398	Y	130,470	(129,971)	100%	215,715
Retail East	Retail	9	622	7.5	0.12	145	100%	1,193	Y	1,866	(20,961)	1123%	34,790
Retail West	Retail	6	372	7.5	0.12	86	100%	112	Y	1,116	(1,975)	177%	3,279
Fire Command Roo	Mechanical Room	-	203	-	0.06	12	100%	16	Y	-	(278)		462
Gas Meter Room	Mechanical Room	-	78	-	0.06	5	100%	6	Y	-	(107)		177
Elevator Lobby	Lobby	60	397	5.0	0.06	322	100%	675	Y	11,910	(11,864)	100%	19,692
Public Restroom	Restroom	-	150	-	0.06	9	100%	980	Y	-	(17,218)		28,577
Exit Passageway	Corridor	-	319	-	0.06	19	100%	31	Y	-	(538)		893
Upper Lobby	Lobby	297	1,979	5.0	0.06	1,603	100%	3,687	Y	59,370	(64,775)	109%	107,509
Stairwell East	Corridor	-	640	-	0.06	38	100%	50	Y	-	(877)		1,456
Stairwell West	Corridor	-	640	-	0.06	38	100%	50	Y	-	(877)		1,456
Totals						5,800		14,198		204,732	(249,443)		414,005

Restaurant

Zone Name	Zone Type	People [#]	Area [SF]	People OA Rate [CFM]	Area OA Rate [CFM]	Breathing Zone OA [CFM]	Ez [%]	Delivered OA [CFM]	Meets LEED 30% [Y/N]	Space Latent Load [BTUh]	Latent Load Handled [BTUh]	% Load Handled [%]	Sensible Capacity Added [BTUh]
Dining Area	Restaurant	339	4,848	7.5	0.18	3,418	100%	9,416	Y	93,324	(92,971)	100%	75,254
Kitchen	Kitchen	8	1,680	-	0.70	1,176	100%	1,529	Y	10,250	(15,095)	147%	12,218
Men's Restroom	Restroom	-	70	-	0.06	4	100%	5	Y	-	(54)		44
Women's Restroom	Restroom	-	70	-	0.06	4	100%	5	Y	-	(54)		44
Corridor	Corridor	-	678	-	0.06	41	100%	53	Y	-	(522)		423
Totals						4,643		11,009		103,574	(108,696)		87,982

Exhaust Calculations

Office Floors 5 - 30						
Zone Name	Zone Type	Area Exhaust Rate [CFM/SF]	Unit Exhaust Rate [CFM/unit]	Zone Area [SF]	Zone Units [#]	Total Exhaust [CFM]
Men's Bathroom	Public Restroom	-	50	-	4	200
Women's Bathroom	Public Restroom	-	50	-	4	200
Pantry	Kitchenette	0.30	-	158	-	47
Copy Room 1	Copy / Print Room	0.50	-	90	-	45
Copy Room 2	Copy / Print Room	0.50	-	107	-	54
				Total Exhaust per Floor		546
				Number of Floors		25
				Total Office Exhaust		13,648

Upper and Lower Lobby						
Zone Name	Zone Type	Area Exhaust Rate [CFM/SF]	Unit Exhaust Rate [CFM/unit]	Zone Area [SF]	Zone Units [#]	Total Exhaust [CFM]
Restaurant Kitchen	Commercial Kitchen	0.70	-	1,090	-	763
Lobby Interactive Toilet	Private Restroom	-	25	-	1	25
Restaurant Men's Toilet	Private Restroom	-	25	-	1	25
Restaurant Women's Toilet	Private Restroom	-	25	-	1	25
Storage Closet	Storage Closet	1.50	-	-	-	-
				Total Exhaust		838

Underground Parking Garage						
Zone Name	Zone Type	Area Exhaust Rate [CFM/SF]	Unit Exhaust Rate [CFM/unit]	Zone Area [SF]	Zone Units [#]	Total Exhaust [CFM]
Parking Garage - 01	Parking Garage	0.75	-	6,884	-	5,163
Parking Garage - B1	Parking Garage	0.75	-	11,547	-	8,660
Parking Garage - B2	Parking Garage	0.75	-	15,126	-	11,345
Parking Garage - B3	Parking Garage	0.75	-	15,126	-	11,345
Men's Locker Room	Locker Room	0.50	-	270	-	135
Women's Locker Room	Locker Room	0.50	-	250	-	125
Men's Restroom	Public Restroom	-	50	-	3	150
Women's Restroom	Public Restroom	-	50	-	3	150
				Total Exhaust		37,072

Bio-methane Facility						
Zone Name	Zone Type	Zone Area [SF]	Average Zone Height [ft]	Zone Volume [CF]	Zone Airflow [ACH]	Zone Airflow [CFM]
Tank Room	Fuel Production	9,530.00	11	104,830	20	34,943
Finishing Room	Fuel Production	700.00	11	7,700	20	2,567
				Total Exhaust		37,510

Appendix H

Radiant Cooling Panel Analysis

Radiant Ceiling Panel Parameters

Material Properties			Panel Properties		
Overall U-value	4	[BTU/h/ft2/F]	Tube Diameter	0.5	[in]
Conductivity	118	[BTU/h/ft/F]	Tube Spacing	6	[in]
Volume Flow Rate	1	[gpm]	Fin Thickness	0.125	[in]
Entering Cooling T	67	[F]	Panel Area	48	[ft2]
Cooling Cp	1.000	[BTU/lbm/R]	Panel Perimeter	32	[ft]

Panel Heat Flux Calculation

Season	Heat Transfer Type	Panel Temp. [F]	AUST [F]	Air Temp. [F]	Panel Area [ft2]	Panel Perimeter [ft]	Equivalent Diameter [ft]	Heat Flux [BTU/h/ft2]
Cooling	Radiative	69.23	80.10	-	-	-	-	(9.95)
	Convective	69.23	-	78.00	48.00	32.00	6.00	(6.26)
							Total:	(16.21)

The radiant ceiling panels were modeled using a procedure from ASHRAE as well as Conroy and Mumma (2001). Their system design equations were used in order to configure the chilled ceiling for the office floor to match the performance characteristics of the plate-and-frame heat exchanger and cooling towers which serve the panels. Design parameters were modified in order to meet space requirements in the Typical Office Floors as well as to ensure cooling loads are met during Design Day cooling loads. IES Virtual Environment was used to analyze room surface temperatures for the purpose of finding the Average Unconditioned Surface Temperatures (AUST). Tube spacing and diameters were determined by looking up typical radiant panel geometries.

Panel Average Temperature

Season	Panel Assembly	Overall Heat Transfer Coefficient [BTU/h/ft2/F]	Panel Area [ft2]	Volume Flow Rate [gpm]	Mass Flow Rate [lbm/h]	Water Specific Heat [BTU/lbm-F]	Entering Water Temp. [F]	Leaving Water Temp. [F]	ΔT [F]	Air Temp. [F]	Heat Removal Factor	Panel Temp. [F]
Cooling		4	48.00	1.00	500.4	1.000	67.0	70.4	3.4	78.0	0.80	69.2

Radiant Slab Design Equations

General Heat Flux Equations

$$\dot{q}_r = 0.15 \times 10^{-8}\left[\left(t_{p,mean}\right)^4 - (AUST)^4\right]$$

$$\dot{q}_c = 0.31\left(t_{p,mean} - t_a\right)^{0.31}\left(t_{p,mean} - t_a\right)$$

Mean Panel Temperature

$$t_{p,mean} = t_{f,in} + \left\{\frac{\dot{m}C_p\left(t_{f,out} - t_{f,in}\right)}{AF_R U}\right\}(1 - F_R)$$

Panel Heat Removal Factor

$$F_R = \frac{\dot{m}C_p\left(t_{f,out} - t_{f,in}\right)}{\left\{A\left[-U\left(t_{f,in} - t_a\right)\right]\right\}}$$

Design Equations (cont.)

Leaving Water Temperature

$$t_{f,out} = t_a + \left(t_{f,in} - t_a\right)e^{\frac{-UAF'}{\dot{m}C_p}}$$

Panel Efficiency Factor

$$F' \cong \frac{[D + (w - D)F]}{w}$$

Fin Effectiveness

$$F = \frac{tanh\left[\frac{1}{2}\sqrt{\frac{U_o}{k\delta}}(w - D)\right]}{\frac{1}{2}\sqrt{\frac{U_o}{k\delta}}(w - D)}$$

Appendix I

Cooling Tower Analysis

Cooling Tower Definition

Manufacturer	Marley	Fan Motor Speed	1800 rpm
Product	NC Steel	Fan Motor Capacity per cell	30.00 BHp
Model	NC8403SLN4	Fan Motor Output per cell	30.00 BHp
Cells	4	Fan Motor Output total	120.00 BHp
CTI Certified	No	Air Flow per cell	104900 cfm
Fan	7.000 ft, 8 Blades	Air Flow total	419700 cfm
Fan Speed	473 rpm, 10402 fpm	Static Lift	12.234 ft
Fans per cell	1	Distribution Head Loss	0.000 ft
		ASHRAE 90.1 Performance	45.7 gpm/Hp

Model Group: Quiet Fan (L)
Sound Pressure Level: 81 dBA (Single Cell), 5.000 ft from Air Inlet Face. See sound report for details.

Conditions

Tower Water Flow	3917 gpm	Air Density In	0.07386 lb/ft³
Hot Water Temperature	68.00 °F	Air Density Out	0.07477 lb/ft³
Range	3.00 °F	Humidity Ratio In	0.00905
Cold Water Temperature	65.00 °F	Humidity Ratio Out	0.01389
Approach	3.00 °F	Wet-Bulb Temp. Out	66.29 °F
Wet-Bulb Temperature	62.00 °F	Estimated Evaporation	18 gpm
Relative Humidity	50.0 %	Total Heat Rejection	5875100 Btu/h
Capacity	95.0 %		

- This selection is within tolerance but does not satisfy your design conditions.
- The performance for this selection is not guaranteed because the approach is less than 5 °F.
- This selection is not CTI Certified because: the range is less than 4 °F, the approach is less than 5 °F.

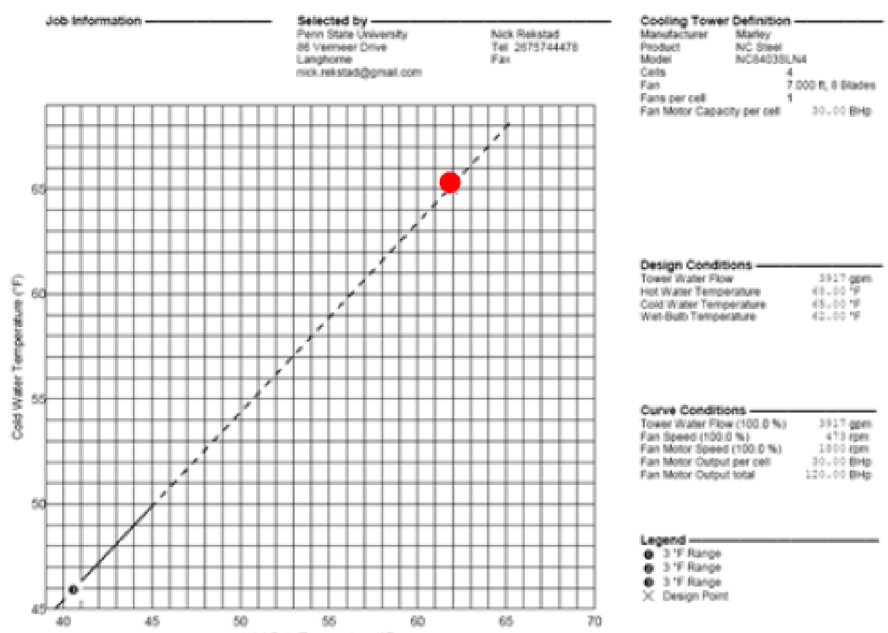
Weights & Dimensions

	Per Cell	Total
Shipping Weight	7440 lb	29770 lb
Heaviest Section	7440 lb	
Max Operating Weight	16770 lb	67090 lb
Width	18.170 ft	18.170 ft
Length	8.400 ft	34.462 ft
Height	11.939 ft	

Minimum Enclosure Clearance

Clearance required on air inlet sides of tower without altering performance. Assumes no air from below tower.

Solid Wall	13.480 ft
50 % Open Wall	10.358 ft



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ACADEMIC VITA

Nicholas M. Rekstad
nick.rekstad@gmail.com

Education:

Bachelor of Architectural Engineering, Penn State University, Spring 2014
Master of Architectural Engineering, Penn State University, Spring 2014
Minors in Architectural Studies and Information Science and Technology
Honors in Architectural Engineering
Thesis Title: Mechanical Engineering of a Commercial High-rise which Achieves Near-Net Zero Energy, Water, Waste and Emissions
Thesis Supervisor: Moses Ling

Honors and Awards:

Willis H. Carrier National Scholarship
Jack Everetts Memorial Scholarship
Evan Pugh Scholar
Dean's List 10/10 semesters

Professional Experience:

Mechanical Engineering Intern at **Arup**, Summer 2013
Supervisor: Joshua Yacknowitz

Engineering Design Intern at **Southland Industries**, Summer 2013
Supervisor: Scott Winkler

Publications and Papers:

Rekstad, Nicholas, Mohammad Heidarinejad, Joshua Wentz, and Jelena Srebric. "Energy Performance Analyses of Campus Buildings over Heating and Cooling Seasons." *COBEE Conference Proceedings*. Boulder: University of Colorado, 2012. Print.

Rekstad, Nicholas, Ute Poerschke, and Jelena Srebric. "Microclimate Analyses for the Design of Building-Integrated Wind Turbines." *AEI Conference Proceedings*. State College: Architectural Engineering Institute, 2013. Print.

Association Memberships/Activities:

President, ASHRAE
President, Student Society of Architectural Engineers
Penn State Lightweight Rowing