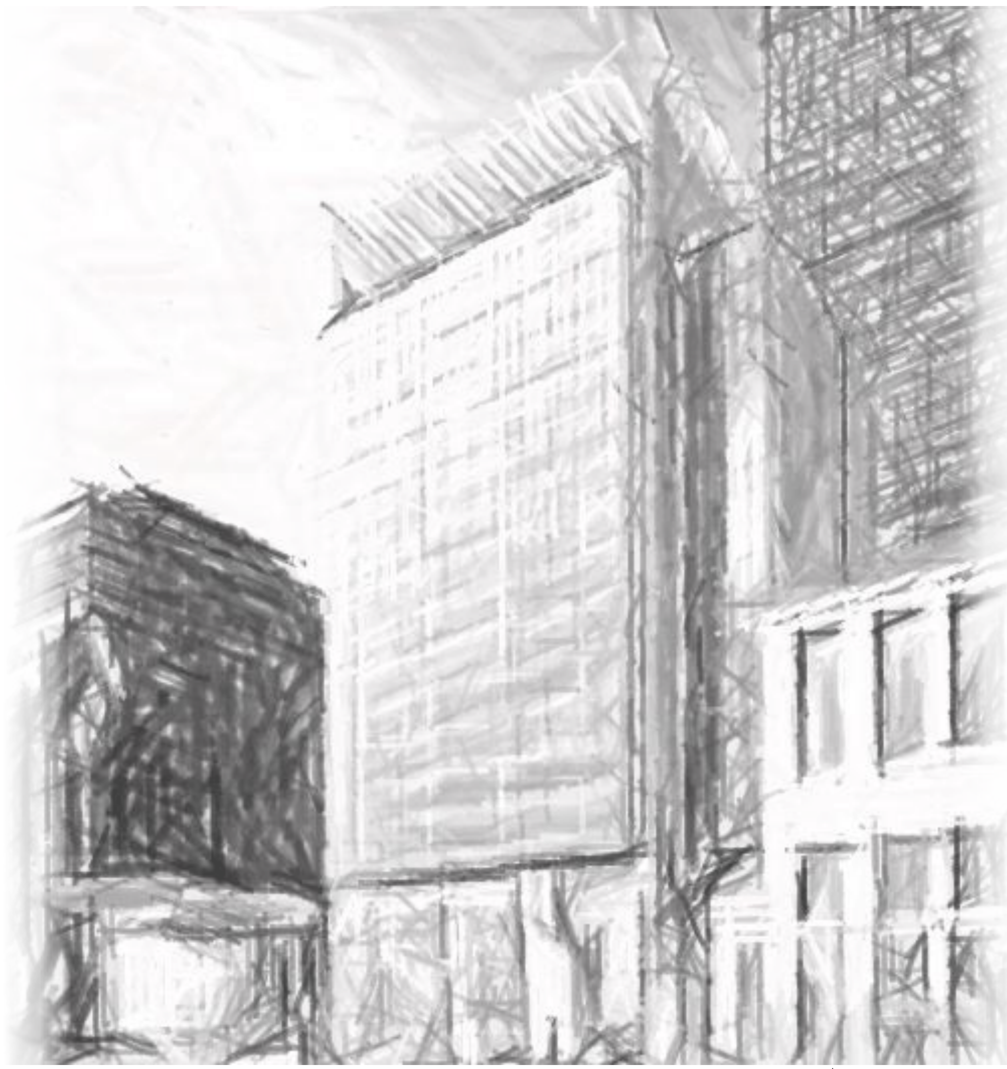
888 Boylston Street

Boston, MA | Team 09-2016



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ORGANIC ECONOMIC INTEGRATE ENGAGE SUSTAIN

Architectural Engineering Institute
Student Design Competition 2016

Integration | Structural | Mechanical | Electrical

Included Design Narratives

I. Building Integration Design Narrative
II. Structural Design Narrative
III. Mechanical Design Narrative
IV. Electrical Design Narrative

Naming Conventions - Graphics

Figure E . 3

Figure
Table
Equation

– Position in document

E – Electrical Systems Narrative
I – Building Integration Narrative
M – Mechanical Systems Narrative
S – Structural Systems Narrative

Naming Conventions – Appendices

Appendix S M . 3

Appendix S – Supporting Documents
Drawing D – Drawings

– Position in document

E – Electrical Systems Narrative
I – Building Integration Narrative
M – Mechanical Systems Narrative
S – Structural Systems Narrative

Integration | Structural | Mechanical | Electrical

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Building Integration Narrative

Building Integration Narrative

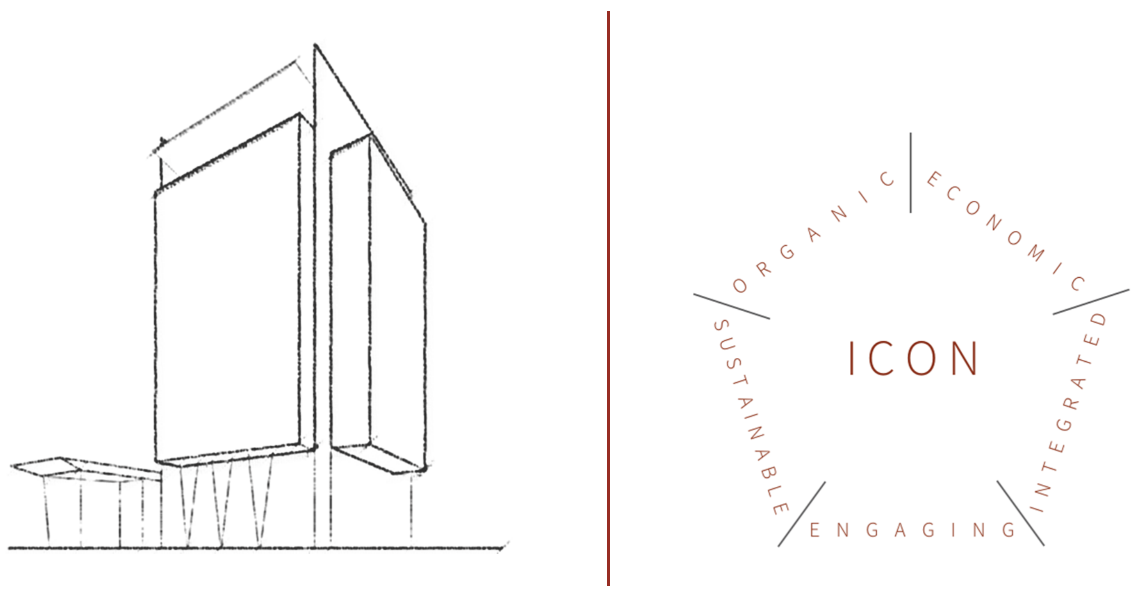
TEAM 09-2016 | AEI STUDENT DESIGN COMPETITION

EXECUTIVE SUMMARY

Design Group 09-2016 is a multi-discipline consulting firm that specializes in structural, mechanical, and electrical designs. The design team utilizes the latest and most innovative technologies and techniques to provide their clients with efficient buildings that serve as icons of the sustainable design ideology.

Design Group 09-2016 has created the following design development document to outline the design goals and engineering systems for the multi-use 888 Boylston Street project in Boston, Massachusetts. 888 Boylston Street rises from a two-story below-ground parking structure to a three-story retail space capped by a 14-story office space. 888 Boylston Street is set to serve as an icon for the City of Boston through both its architecture and the design of its building engineering systems.

The design team employs comprehensive interdisciplinary collaboration to integrate engineering systems to a standard that is fitting for modern sustainable design. Design Group 09-2016 views a sustainable design as a facility that not only is efficient but also creates as minimal of a footprint on its surrounding environment as possible through the reduction of waste and consumption of resources. This organic relationship between systems creates a building capable of producing significant economic benefits for owners and allows for the full engagement of employees and clients alike.



888 Boylston Street Design Philosophy

THE TEAM

Overview

The design team is composed of six graduate-level architectural engineering students that each have a holistic understanding of building design. The six team members are split amongst one of three discipline-specific design teams which include Structural, Electrical/Lighting, and Mechanical specialties. Each design team is assisted by one undergraduate student each to aid in the design and drafting processes. Although the discipline design teams are responsible for their own unique engineering systems, all team members come together to collaborate and compose integrated engineering solutions that are not only functional but exceptionally innovative as well.

Industry Consultants

Experience is an essential component of any successful design. For this reason, industry mentors were consulted to give advice in both design and project progression. During each step of the design process, several key meetings were held to ask general questions and to present a progress update. The first of these meetings was held at the conceptual phase to properly align all team members with the project goals. The next major meeting occurred at the 50% design mark in the form of a progress update. Here industry consultants collaborated with the design team and had a round-table discussion covering updates on the project, allowing the industry professionals to provide insight on the team's preliminary design work. Following these progress updates were discipline specific sessions where technical discussions were conducted. Between meetings regular email communications took place, allowing for a fluid question and answer process. Nearing submittal deadlines the design team sent the consultants a 95% narrative for the comments and approval. Overall, the collaboration with the industry consultants allowed for a more realistic, accurate, and supported design.

Integration Ideology

The integration process took many ideas from concepts of integrated project delivery. This delivery approach involves a multi-party agreement between the owner, general contractor, subcontractors, engineers, and architects. All parties agree to work together with a high level of trust in order to create the most economical and reliable systems. Instead of acting as separate teams, all members of the building team act as one unit for a specific project. This collaborative process requires all members of the project team to work in the same space, allowing for fewer traditional meetings, improved communication and fewer instances where redesign was required. Integrated project delivery allows for a far greater whole-building energy and cost savings. The design team followed this practice of continuous collaboration across all disciplines, sharing a common workspace for the vast majority of the 888 Boylston Street design.

Technology Used

The design team used a variety of technologies to effectively coordinate design changes and interdisciplinary RFIs to maximize integration. For modeling, the project team relied heavily on Building Information Modeling or BIM, with Revit 2015 as the modeling software of choice. The capability of Revit to work from a central model set it apart as a clear favorite, allowing the design team to quickly share all technical changes in three dimensions in real-time. This software allowed for enhanced integration across all disciplines as models were cross-checked with a clash-detection feature allowing for a true coordination of systems. Google Drive was utilized for storage of all project material such as preliminary narratives, presentations, calculations, and models, allowing members of all disciplines to access all project information. Communication between group members was organized through the GroupMe mobile messaging application where messages and photos could be sent, shared, and archived in real time between all team members.

Collaboration

Collaboration is a fundamental component of integrated design. This idea drove the design team to begin interdisciplinary collaboration at project onset during the development of high-level design goals. Each discipline presented certain goals that would be otherwise unattainable without the direct and early coordination of building systems between the engineering disciplines and the architectural design. In the case of 888 Boylston Street, individual discipline teams participated in brainstorming sessions to generate sustainable ideas that are currently at the forefront of modern architectural design. These sessions led to an abundance of ideas that were closely aligned to the team's core design philosophy of creating a pioneering icon of modern sustainable design within the heart of Boston, Massachusetts. These goals required collaboration between structural, mechanical, and electrical design teams to be realized at their full potential. For example, the implementation of an exposed structural ceiling required specific types of both mechanical and structural systems. Further coordination was essential to ensure these two engineering systems integrated effectively into the daylighting strategies required by the lighting design team to further boost worker engagement and productivity.

Peer Review

With the complex engineering systems required to fulfill the goal of designing 888 Boylston Street as a low-impact, sustainable facility, came a need for thorough review of all design decisions. The design team developed and implemented a multi-faceted review process in which all design documents were reviewed first by another member of the Design Group 09-2016 team, and secondly by a design engineer at a partner professional firm. To ensure a comprehensive interdisciplinary analysis, the in-house review of each discipline's document was performed by a member of a different discipline, while the industry review was performed by a professional engineer of the same discipline as the document being reviewed.

888 BOYLSTON STREET

The Client

The owner of 888 Boylston Street desires the development and integration of innovative and original solutions to the building systems. The client places emphasis on integrated design that is optimized on a lifecycle basis. Key elements of importance to the client include: energy conservation, environmental consideration, safety, building security, durability, accessibility, cost, productivity, sustainability, and functionality. Resiliency is also provided with respect to local environmental conditions, including provisions for a tenant requiring high-end IT facilities allowing 888 Boylston Street to accommodate world-class financial institutions. The impact on adjoining structures and public ways is also directly addressed.

The Site

The 888 Boylston Street site is located close to downtown Boston and lies approximately 1,800 feet from the Charles River Basin. The building itself is located amongst several other large buildings affecting system placement, daylight performance, and wind pathing, amongst other factors. A prominent and influential building near the site is the Prudential Center to the south. The presence of this building must be carefully analyzed as its shading has a negative impact on the performance of the photovoltaic system on the top of the building. A four story and a thirteen story building respectively lie to the east and west of the site. Boylston Street borders the site to the north, separating 888 Boylston Street from a series of nine story buildings. Many of these buildings adjacent to the site have a large impact on the daylighting of the retail and office spaces requiring systems to be designed accordingly. A small two story below-ground parking structure currently stands on the site and will be incorporated into new facility. While the majority of this parking structure will be demolished to make way for the new building, portions will remain, including the retaining walls, mat foundation, and several smaller mechanical rooms. Additionally, the southwest side of the site is constrained below-grade diagonally by the Interstate 90 Turnpike. The turnpike and accompanying fan room will force the building to be built around it in a way to avoid damages and closures on the turnpike.

The Building

888 Boylston Street is a 17-story high rise building located in Boston, Massachusetts. The building is mixed-use, with retail and office spaces. At approximately 625,000 square feet, various occupancies exist within the building, including a large public lobby, three floors of retail space, 14 floors of office space, and a multi-level underground parking garage. A food hall is located adjacent to the building on the south, and a retail mall is located adjacent to the east.

The Plaza

The street level plaza is an 18,000 square foot space that serves as occupants' first impression of the site, making it a key area of design. The building is setback 65 feet from the north property line and Boylston Street. The plaza presented an opportunity for the team to design a unique focal point that represents the five aspects of the design philosophy: organic, economic, sustainable, integrated, and engaging design. This plaza acts as a literal representation of the client's principles.

Parking Facility

The parking facility is a two level underground garage that connects with the parking garage of the building to the east. The garage is 72,000 square feet and houses approximately 150 parking stalls. The parking facility required significant integration between all design teams to produce a design that fully integrated with the surrounding buildings and public ways.

The Entrance Lobbies

Just as the plaza is a first impression of the site, lobbies act as the first impression of the interior of the building. Between the unique structural storefront modifications to the intricate and engaging lighting systems, these spaces require a high-end and detailed design. The two separate lobbies serve to draw occupants further into the building to visit the food hall or to prepare to enter the offices.

Retail Space

The retail space covers approximately 60,000 square feet over a central portion of the first 3 levels of the building. This retail area has independent front access from both the Street Level plaza and Arcade Level located on the second floor. With a constant stream of new customers coming into the area, the retail space is a highly scrutinized area of the building. A comfortable customer is a good customer; proper and motivating design is critical in these spaces.

Office Space

The office space consists of 355,000 square feet on levels 4 through 17 of the building. The offices have independent front access at both Street Level and Arcade Level. The office space required integration between disciplines with the canted ceilings, the radiant floors, and the workstation usability components to create an inspiring environment for workers who will spend many hours within.

Architectural Changes

There were several changes made to the architecture of the building in the development of the design for 888 Boylston Street to increase to bring increased functionality of the space to a LEED platinum design caused through the integration of all disciplines. As a byproduct of some of the design decisions such as decreasing the floor to floor height, the cost of construction was able to decrease while the keeping the amount of rentable space within the building relatively unchanged. Figure I.1 lists and portrays the unique architectural changes.

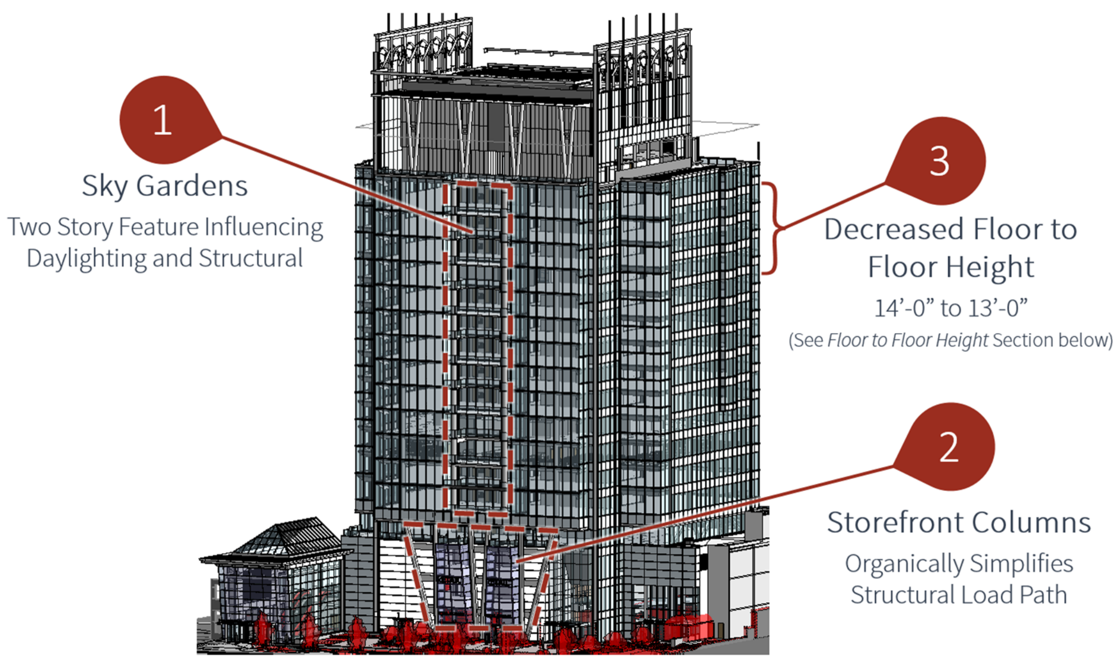


Figure I.1 – North Façade Architectural Changes Summary

<u>Sky Garden</u>

A major architectural innovation implemented at 888 Boylston Street was the addition of the sky gardens - a stunning feature located on the north facade of the building. Each sky garden spans two-floors, with the lower of the two floors serving as a full outdoor courtyard for the occupants of the office floors to enjoy. The upper of the two floors in each sky garden section will have a smaller mezzanine that rings the interior edge of the sky garden, allowing for a small usable exterior space for occupants. The sky garden location organically fits in the structural framing plan with minimal changes to the structure being required. Figure I.2 gives a representation of the Sky Gardens.

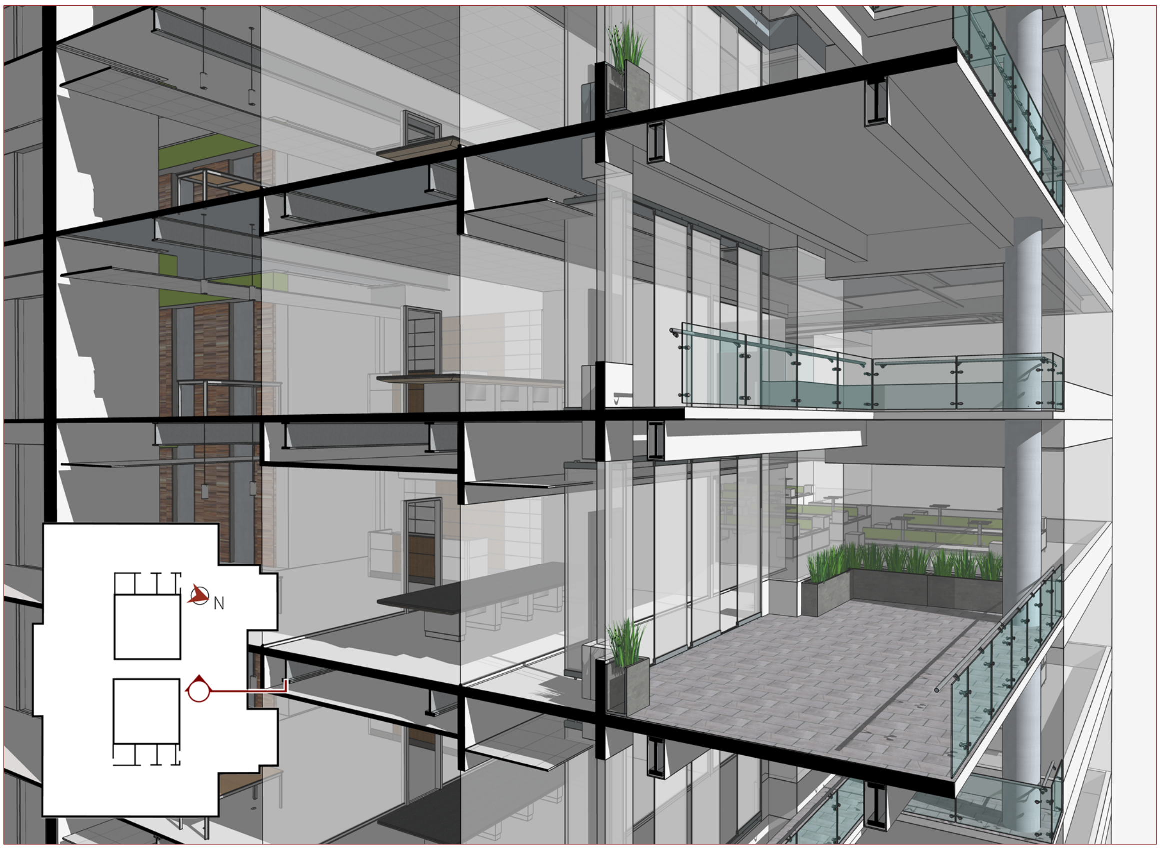
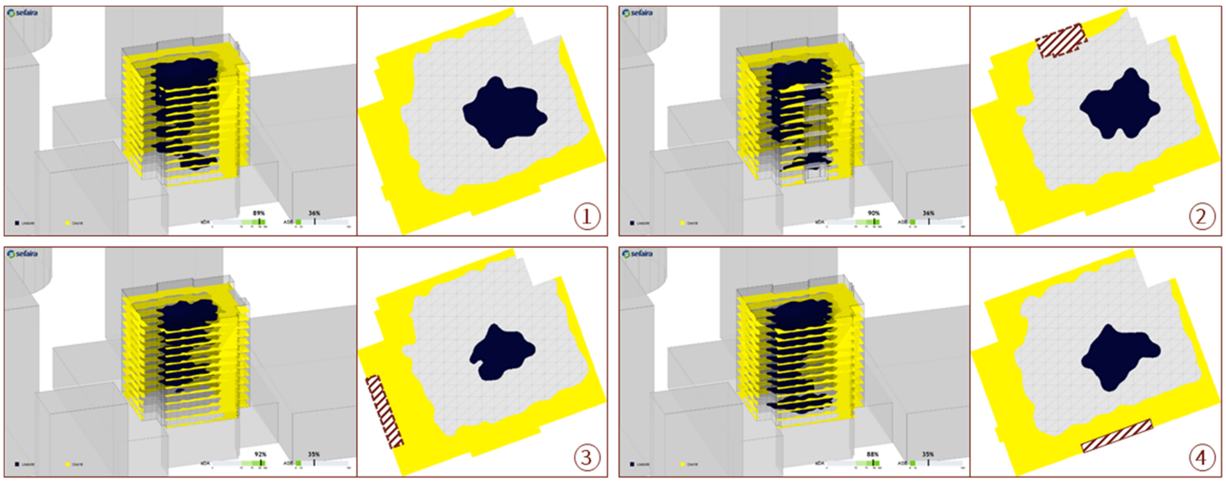


Figure I.2 - Sky Garden Section Cut

The sky gardens also have a positive influence on the daylight penetration of the office floors. The "cutout" created by the gardens allow for deeper penetration of daylight into the workplace, lessening reliance on electric lighting. To fully analyze the benefits of having this sky garden, a daylight study was conducted using an analysis program called Sefaira to determine the best orientation for the sky garden. As seen in Figure I.3, locating the sky garden on either the north or west facades increases the spatial daylight autonomy (sDA) of the entire office space from one to three percent respectively.

While the west facade has the largest increase in spatial daylight autonomy, the sky garden concept is intended to be an icon of sustainability to the public. The north orientation of the sky garden excels at displaying the sustainable design aspects of this architectural feature to all passersby, positively influencing the community. Within the building, this feature provides occupants of the office space with stimulating views of the Boston Back Bay neighborhood, the Charles River, and Cambridge, MA. As an added bonus, users of the sky garden are afforded an excellent perspective overlooking the iconic final stretch of the Boston Marathon as it concludes several blocks to the east on Boylston Street. The percentage of occupied hours where illuminance is at least 28 Fc, measured at 2.95 feet above the floor plate can be found in Appendix SI.1.



Iterative Sky Garden Design

1	- Baseline (No Sky Garden)	SDA: 89%	
2	- North Sky Garden	SDA: 90%	(+1%)
3	- West Sky Garden	SDA: 92%	(+3%)
4	- South Sky Garden	SDA: 88%	(-1%)

Figure I.3 - Daylight Sky Garden Visualizations

Storefront Columns

The original storefront column system started as a structural design challenge, but through interdisciplinary collaboration, it evolved into an architectural opportunity. The outside tower column, supporting 14 stories of office building, originally terminated on a cantilever 10’ past the outside pairs of columns. This required some unique framing back into the structure or a massive plate girder to cantilever out as a support. In order to avoid both poor but possible solutions, the structural design team decided to modify the geometry by sliding the bottom location of the outside pairs of columns toward the center until the inside columns stand vertically. The top of the outside column was moved out to meet the termination point of the outside tower column. This arrangement obviated the massive cantilever, streamlined the load path, and reduced the cost by simplifying the structural system, all while creating a more organic storefront that points up to and through the sky gardens, creating a natural integration between the building lobby storefront and the office building façade. Figure I.3 in the previous section details the integration between the office façade and the storefront system.

KEY ENGINEERING

Floor to Floor Height

An integrated design enabled the floor to floor height to be decreased from 14'-0" to 13'-0". Not only does this greatly reduce the overall material usage throughout the 888 Boylston Street project – saving roughly $1,500,000 in upfront costs – but this reduction also creates a building that is more sustainable through decreased HVAC loads (via reduced volume) and reduced construction time. The design decisions that allowed for the floor to floor height reduction are detailed below.

The use of an active chilled beam system in the office spaces reduced the required airflow into occupied zones, and thus decreased duct size, opening up valuable space within the ceiling areas.

Lighting in a traditional office workspace is either recessed into the ceiling or mounted below the ceiling plane through the use of linear direct/indirect pendant fixtures. To reduce the required depth of the ceiling plane, the lighting design team set a goal of moving the bulk of the lighting systems down from the ceiling cavity through the use of workstation mounted Tambient® lighting fixtures. Not only does this remove bulky fixtures from the ceiling area, but it also eliminates the need for cumbersome electrical conduit related to the lighting system, enabling a more free-flowing and efficient layout of the space's mechanical systems. Additionally, monetary savings were realized through a reduction in conduit and decreased labor costs which are discussed in further detail in the *Electrical Systems Narrative*.

Exposed Ceiling

Exposed ceilings were selected by the design team to maximize the openness of the office floors. The structural framing layout was optimized to create consistent and visually appealing bays with long, deep girders that radiate from the concrete core to the daylit facade and with shallow infill beams to create a more open space. To aid in the architectural functionality of the space, canted ceiling clouds were designed to rest above the work areas within each structural bay to supplement each design discipline due to advantageous properties offered to each set of systems. The canted ceilings allow for daylight to be reflected down onto each individual workstation, while still providing an aesthetic canopy over the working environment. To further improve daylight penetration into the work area the spandrel beams on the North and South sides of the building were designed to be as shallow as possible.

Figure I.4 - Exposed Ceiling Render

Additionally, mechanical equipment, ductwork, and piping is concealed above the panels, with voids left between panels in each structural bay to allow ducts supplying ventilation air to be routed to the exterior edges of the space. The canted ceiling panels aid in dampening sound levels throughout the offices to maintain a pleasant acoustic environment.

Mechanical Equipment

Significant integration between the mechanical, structural, and electrical disciplines occurred when locating and powering the mechanical equipment. The disciplines met regularly to discuss equipment weights, power requirements, and locations in order to determine structural member sizes and electrical system sizing and pathing. With most of the mechanical equipment located in the mechanical penthouse, the electrical team placed a mechanical switchboard within the penthouse electrical room. This switchboard powers the majority of the penthouse mechanical equipment, with the exception of systems required by International Building Code (IBC) 2009 to remain on emergency power. Specifically, elevator ventilation and fire pumps must be on emergency power, while smoke evacuation and ventilation systems are to be placed on legally required standby power. In regards to specific equipment placement, the elevator ventilation exhaust fan is located within the penthouse, while the fire pumps are located on the third floor. Additionally the exhaust fans (coupling as the smoke evacuation fans) are located within the penthouse as well as on the third floor. In the case of a loss of power, all of this equipment will be fed from a 1 MW generator located on the rooftop of the building. The mechanical design team provided a coordination table (as seen in Table I.1 below) to provide all other teams with a concise yet tailored summary of key data regarding the mechanical equipment within the building streamlining design and helping ensure a safe design.

GENERAL			STRUCTURAL		ELECTRICAL				
TYPE	#	LOCATION	WEIGHT (lb.)	L x W x H (in.)	MCA	MOCP	FLA	HP	V/P/H
AHU (WITH SUPPLY)	2	PENTHOUSE	36,000	254 x 182 x 178	-	-	93.1	17.9	480/3/60
FAN (EXHAUST)	4	PENTHOUSE	800	58 x 58 x 69	-	-	-	7.5	480/3/60
CHILLER	4	PENTHOUSE	11,030	152 x 36 x 69	335	400	-	-	480/3/60
BOILER	6	PENTHOUSE	1,560	38 x 29 x 80	-	-	6.2	-	480/3/60
COOLING TOWER	1	PENTHOUSE	2,980	130 x 130 x 90	-	-	7.3	5	480/3/60
PUMP (HOT WATER)	1	PENTHOUSE	400	25 x 12 x 25	-	-	-	10	480/3/60
PUMP (CHILLED WATER)	1	PENTHOUSE	1,000	53 x 25 x 32	-	-	-	40	480/3/60
PUMP (FIRE)	1	GROUND	400	84 x 30 x 21	-	-	-	125	480/3/60
PUMP (DOMESTIC)	1	GROUND	470	42 x 19 x 12	-	-	-	30	480/3/60
PUMP (SEA LOOP)	1	GROUND	4500	87 x 36 x 43	-	-	-	250	480/3/60

Table I.1: Mechanical Coordination Table

Lighting Fixtures and Controls

Efficacious luminaires coupled with photosensor and occupancy sensor lighting controls help achieve a low lighting power density throughout the building. This allows for significantly reduced loads for both the mechanical and electrical systems. For the mechanical team, less cooling is required to cover the sensible heat gain from the luminaires. For the electrical team, the electrical panels can be downsized leading to savings in the installation of panels.

The prolific use of low voltage direct current luminaires throughout the office floors in conjunction with Tambient® fixtures at each workstation present numerous benefits in simplifying the installation process of the lighting fixtures within 888 Boylston Street. The Class-2 48V circuiting powering the downlights and pendants throughout the office greatly reduce the need for licensed electricians during the construction process, providing a significant monetary savings to the owner. Additionally, the proprietary Tambient® lighting control system employs prolific use of RJ-45 cabling and is powered via 120V cord, further reducing the need for licensed electricians across 888 Boylston Street. Refer to the *Electrical System Narrative* for more information on lighting fixtures and controls utilized.

In-floor Systems

The intricate floor construction showcased another area where detailed integration was required between all design teams. The electrical design team is specifying in-floor poke through electrical boxes to create a visually pleasing and convenient space all while ensuring future flexibility. The mechanical team is also specifying an in-slab radiant heating system to promote occupant comfort and harness the benefits of an all-water heating system. The conduit for low voltage and power cabling will be run underneath the slab in the floor below and up through the poke-through device. The conduit will be painted to match the slab color to blend in with structural system. This required a high level of coordination regarding the placement of poke through boxes around in-slab radiant floor system, from the initial planning phase especially to final system layout. While complex, this combined in-floor system has numerous benefits for both the mechanical and electrical designs. Utilization of the two in-floor systems will also require the structural team to specify a floor construction that accommodates the installation of these systems in regards to durability, depth, and insulating properties preventing heat leakage across floors. The poke-through boxes used by the electrical team are rated for two hour fire protection which aligns with the structural system where slabs require two hour fire ratings.

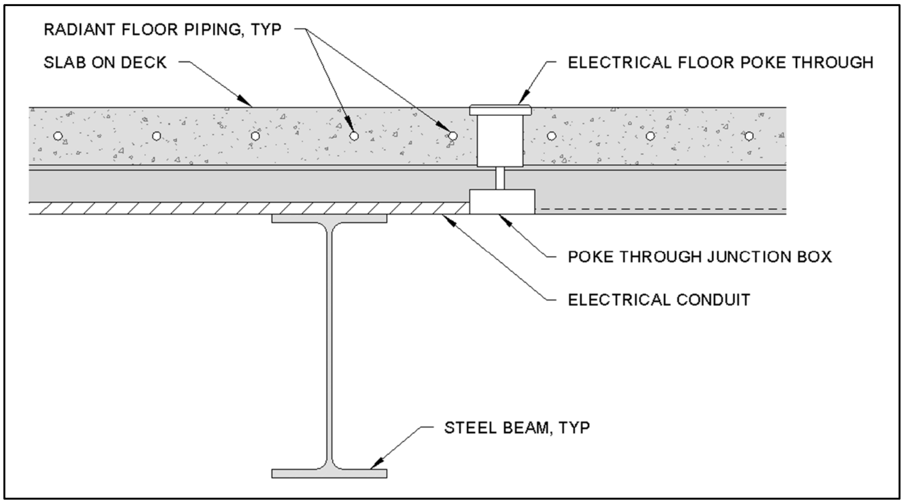


Figure I.5 - In-Floor System Coordination

Daylight Delivery Systems

Coordination between the structural, lighting, and mechanical teams began very early in the conceptual planning regarding enhancing daylight delivery into the office work areas. The structural depth of the floors in the office spaces was reduced at the spandrel locations around the exterior of the building to allow for more daylight access to the open office spaces. This provides an open and organic environment, improving collaboration, engagement, and the overall health of the space's occupant.

Sea Loop

The mechanical system of 888 Boylston Street will utilize a sea loop located in the Charleston River as its main source of heat rejection. This sea loop portion of the Hybrid Loop Heat Rejection System (Described in detail within the *Mechanical Design Narrative)* is one of the most influential of all engineering systems within the building due to its sheer size and ability to reduce consumption of energy and natural resources. The sea loop required coordination between the electrical and mechanical teams to ensure that proper pump function is maintained between the building and the sea loop. The powerful pumps that are integral to this system must be fed with the proper amount of power as specified by the mechanical team. Through coordination with the local electrical utility company, the nearest utility transformer to the river is tapped off of and fed to the pumps eliminating the need to run conduit from the building reducing construction costs and duration, helping minimize the impact that this system has on the public ways in Boston.

Facade System

A major integration aspect of the design of 888 Boylston Street was the curtain wall system used throughout the building. As the curtain wall composes a majority of the facade of the building the mechanical, electrical, and structural teams were all heavily involved within the design of said system. For the mechanical team, the solar heat gain and thermal insulation of the glass impacts the cooling and heating requirements of the building. For the lighting team, the control of the entering daylight can allow for a reduction in the lighting power requirements however it can also become an issue with visual comfort within the office and retail spaces from direct glare. For the structural team, the issue began with determining the deflection limits for the spandrel beams and the construction of the system.

To determine an adequate system, the fenestration design program COMFEN was used to determine the glare, illuminance, and energy usage of various curtain wall systems. Four total window systems were compared. Window system #1 was the baseline and had a curtain wall composed of a 6mm clear window. Window System #2 was a curtain wall system composed of Solarban® 70XL Solar

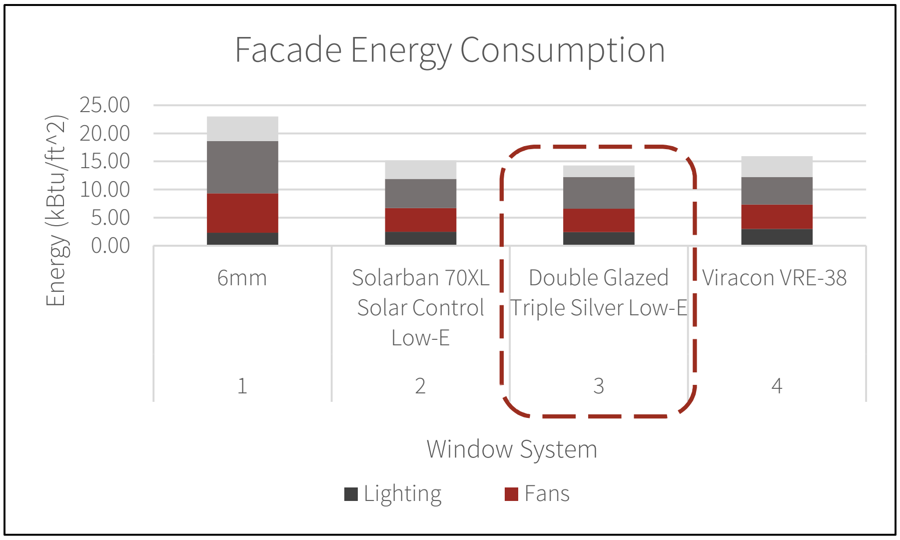


Figure I.6 - Facade Energy Comparison

Control Low-E Glass. Window System #3 was a curtain wall system composed of a Double Glazed Triple SIlver Low-E (Argon) window. Window System #4 was a curtain wall system composed of a Viracon VRE-38 windows from the simulation a daylight and energy usage system was found. See Figure I.6 for the energy comparison between systems.

From the simulation, the team decided to use Window System #3 or the Double Glazed Triple SIlver Low-E (Argon) window for the curtain wall as the building's projected energy usage is the lowest in this scenarios, and the cost for the system is the same when using both Window Systems #2 and #3.

Sawtooth Façade

This unique feature added to the south façade of 888 Boylston Street not only enhances the building architecturally, but also creates a more sustainable design through numerous intuitive design decisions that culminated from discussions between all three design teams. By sloping the south curtain wall inward on each office floor, the building itself acts as an inherent shade from the sun as well as providing a two foot ledge where photovoltaic panels are placed. This southern ledge provides an excellent location for the photovoltaic panels as it allows for the optimal orientation of panels towards the sun and increases the total solar energy production on 888 Boylston Street by a massive 134%. Unlike a traditional building integrated photovoltaic system (BIPV), this ledge gives space for the panels to be mounted at a fixed angle of 42.3° (Boston latitude) to maximize solar gain. The fixed axis photovoltaic panels provide a reduced initial cost as compared to comparable façade mounted BIPV systems, and remove the maintenance issues associated with PV systems mounted into the curtain walls themselves. Figure I.5 gives perspective of the Sawtooth Façade as well as the ceiling coordination between the canted ceiling, structural beams, and chilled beam system. See the section on Drawing DS.7 in the *Structural Systems Narrative* for a structural section of the Sawtooth Façade.

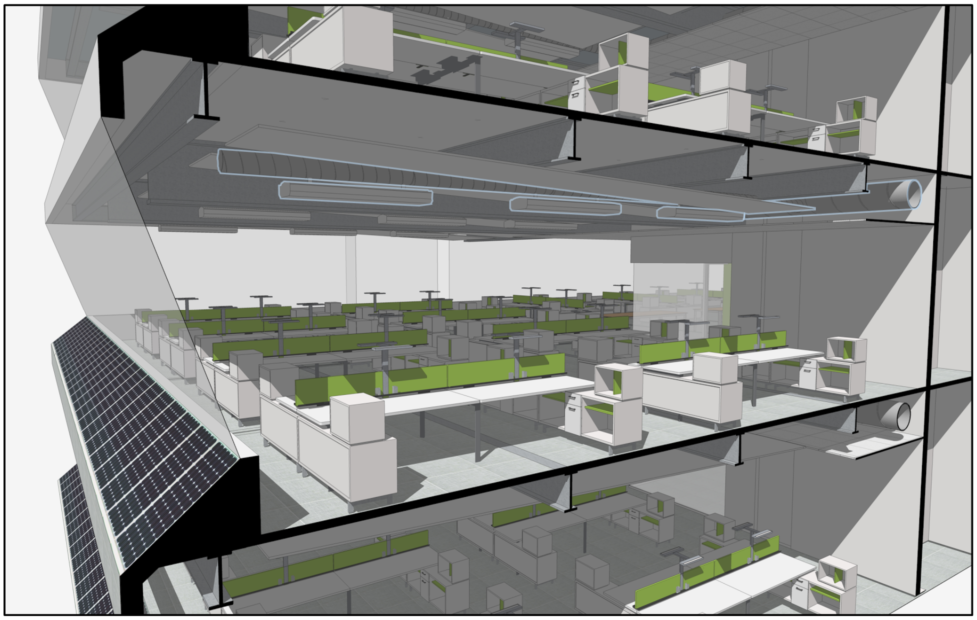


Figure I.7 - South Facade Integrated Systems Section

INTEGRATION AND IMPACT ON SURROUNDING BUILDINGS AND PUBLIC WAYS

As the largest component of the entire project, the hybrid heat rejection loop (specifically the sea loop) requires careful preparation to ensure that its construction remains as inconspicuous as possible to the community. Modern horizontal directional boring techniques will be used to place the below-grade piping for the return and supply condenser water flows between the sea loop and the facility. To reduce the amount of boring involved, the electrical requirements for the sea loop pumps will be satisfied at river location rather than via a long conduit run from 888 Boylston Street.

The building at 888 Boylston Street fills one of the last undeveloped areas in the bustling commercial and residential Back Bay neighborhood. In order to mitigate the impact of a large construction site on the surrounding community, several construction methods are recommended. The first is the site should abide by all city ordinances limiting the dust, noise, traffic, and vibrations during the times when construction can occur. For Boston, these are times are 7:00 AM to 6:00 PM. Surface parking is limited in the surrounding streets and neighborhoods, so construction workers should be given incentives to either ride public transportation or carpool. Finally, a community liaison should be put in place to inform the public about upcoming construction traffic issues and to field complaints at all hours of the day.

888 Boylston Street is to be structurally isolated from all adjacent buildings although they are not architecturally isolated. With little information given relating to the construction of the surrounding buildings, the long-term deflections of the surrounding buildings cannot be adequately determined. In order to guarantee the structural reliability of the 888 Boylston Street far into the future, it is essential to isolate the structural system. This isolation has the added benefit of reducing the amount of required construction in and around the adjacent buildings helping their owners reduce downtime, maintain sales, and granting the public more space.

With part of the building cantilevered over the Interstate 90 turnpike, a major concern was the impact that construction would have on this road section. The design team was aware of this early during conceptual planning, and designed the structural systems specifically around the interstate and existing buildings to avoid any interstate closures.

RESILIENCY WITH RESPECT TO LOCAL ENVIRONMENTAL CONSIDERATIONS

Safety and security of the building occupants are important design goals for 888 Boylston Street. The project is designed to resist increased wind loads for both story drift and strength (100 year mean recurrence interval) to keep the structural system safe for occupants and the curtain wall system sealed to protect building equipment from damage, and the project is designed to provide 48 hours of run-time for critical I.T. loads in case of utility outages that may not only occur randomly, but also may accompany a disaster, man-made or natural. This guarantee of uninterrupted critical IT function opens the doors of 888 Boylston Street to numerous high-end financial or data companies that would otherwise be unable to occupy this space. In order to meet the project requirements of a minimum of 48 hours of run-time in the event of utility outages and meet the requirements of fault tolerance, the optional standby systems feeding the data and IT loads were designed to meet the strict Tier IV data center requirements.

A Tier IV rating signifies that there will be a 2N level of redundancy in the electrical and mechanical systems (Note this IT system is *not* mandatory but is ready to be implemented per client requirements). The Tier IV system requires two standalone utility electrical services, two standalone generators, two standalone chillers, and two standalone computer room air handlers (CRAHs) specifically for the IT/Data loads making this system a perfect illustration of the impact of interdisciplinary coordination. See the *Electrical Design Narrative* for a detailed description of the redundant electrical system used within this design, see the *Mechanical Design Narrative* for a full description of the components and design considerations involved in creating this Tier IV system, and see the *Structural Design Narrative* for the design approach for the increased wind loads on the reinforced concrete shear wall core.

SUSTAINABLE DESIGN AND CONSTRUCTION

Public Sustainability Knowledge Initiative

The Public Sustainability Knowledge (PSK) Initiative is a community-focused educational program used to promote sustainable lifestyles in everyday urban environments. The owner of 888 Boylston Street, Bryan Koop, was quoted at the Real Estate Finance Association Awards Banquet as saying, “Not all companies are ready for the new tactics in creating better and sustainable workplaces, but I believe the customer will always respond to the best products, and we are big listeners to the workforce - we need to be … now I truly feel that through understanding sustainability I impact people’s lives through real estate and the space they acquire.” With these words in mind, the design team felt compelled to realize Mr. Koop’s vision through the development of the PSK Initiative outlined in Figure I.8.

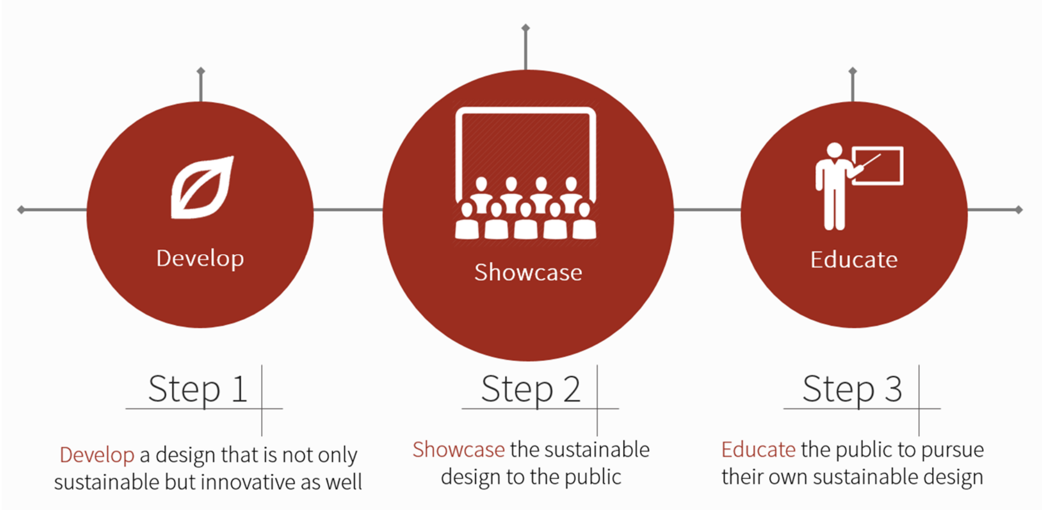


Figure I.8 - Public Sustainability Knowledge Initiative Steps

Develop, Showcase, and Educate. Simple yet powerful ideas that through the PSK Initiative make 888 Boylston Street an icon of sustainability and a staple about how the world should aspire to create its buildings. This program showcases the use of multiple sustainable systems that are highly visible to the public’s eyes in an engaging and dynamic display. This allows the community both inside and outside of the building to learn and follow the sustainable example set by 888 Boylston Street, as the public is able to see sustainability through visual feedback of the energy generated from alternative power sources. While sustainability was the main intent of many of the systems implemented in 888 Boylston Street, cost considerations were also weighed to make a final value engineering decision. See the *Mechanical and Electrical Design Narratives* for information on each system's energy savings and payback periods.

Rainwater Collection

With water becoming a scarcity in numerous locations across the planet, water conservation needs to become a larger part of the public's everyday lives. For this reason, the Public Sustainability Knowledge Initiative begins at the top of 888 Boylston Street at the penthouse. On the penthouse lies a storage tank that collects and stores rainwater. The collected rainwater is fed all the way down from the top of the building through a pipe to an underground storage tank under the fountain in the plaza. The stored water is then used to supply water for the fountain. In order to show the public what is happening with the rainwater collection, a micro-turbine is installed alongside the pipe. When the rainwater drops through the pipe the turbine will spin creating energy. The energy created is then fed to green colored LED lights in the plaza in front of the building. By seeing the light being emitted from the light fixture, the public will know that rainwater is being collected to be used. With this initiative, the public will become aware of rainwater collection bringing a new age of water conservation awareness.

Solar and Wind Energy Production

The second component of the Public Sustainability Knowledge Initiative involves renewable sources of energy. With an increasing amount of carbon being released into the atmosphere on a global scale, the movement to create electrical energy from nonrenewable sources has become increasingly prevalent. By using renewable energy sources, these carbon emissions can be reduced paving the way for a healthier Earth. For this reason, 888 Boylston Street uses two primary sources of renewable energy: photovoltaics and wind. For the photovoltaic energy production, three PV arrays are located on the penthouse of the building along with PV arrays on each office façade. For the wind energy production, fourteen wind turbines are installed on the penthouse level. These sources feed into the main distribution of the building to aid in the powering of equipment. See Appendix SI.2 for a visualization of the renewable sources as well as their energy production.

Figure I.9 - Energy Screen Display in Office Entrance

For the PSK Initiative, a meter is connected to the two renewable systems that collects and stores data on the energy production from each of the two systems, which is then used to calculate other statistics such as carbon emissions saved, daily energy production, yearly energy production, and annual monetary savings. These statistics will be displayed on the slanted wood ceiling in the Office Lobby through ceiling-mounted projectors, displaying all of this information directly to the public's eye. With this knowledge, the many thousands of visitors to 888 Boylston Street can see the real-time benefits of renewable energy sources. See Figure I.9 for a visualization of this PSK display.

LEED

LEED 2009 Building Design + Construction for New Construction was used to determine an estimated building LEED certification level. LEED credits were assigned based on reasonable achievability. The design team acquired 87 of the possible 110 points. This is a LEED Platinum building design. See Appendix SI.3 for the LEED Checklist.

For "Sustainable Sites," points were obtained through sustainable design of the parking structure and use of a pre-developed site. For "Water Efficiency," points were obtained through design of the sky gardens and the rainwater collection system. For "Energy and Atmosphere," points were obtained through the reduction of energy use by over 50% of the baseline and the use of photovoltaics to produce on-site renewable energy. For "Materials and Resources," points were obtained through the use of local and recyclable materials. For "Indoor Environmental Quality," points were obtained through the implementation of carbon dioxide monitors, the use of low VOC-emitting materials, and simulation of the daylight available throughout the building. For "Innovation and Design Process," points were obtained through the utilization of the sea loop, phase change materials, and the unique Sawtooth Facade.

CONCLUSION

The structural, mechanical, and electrical teams coordinated their individual discipline goals throughout the entire design process to create an integrated building that follows a simple yet powerful philosophy to create a showcase of modern sustainable design in 888 Boylston Street. The level of detail and collaboration across the entirety of the design team led to the development of the Public Sustainability Knowledge Initiative that incorporates the citizens of Boston, both within and around the building into the idea of maintaining an engaging, economic, organic, and innovative workplace for decades to come. This building is an icon not only to Boston, but to the entire notion of achieving sustainability through integrated engineering design.

Integration | Structural | Mechanical | Electrical

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Structural Systems Narrative

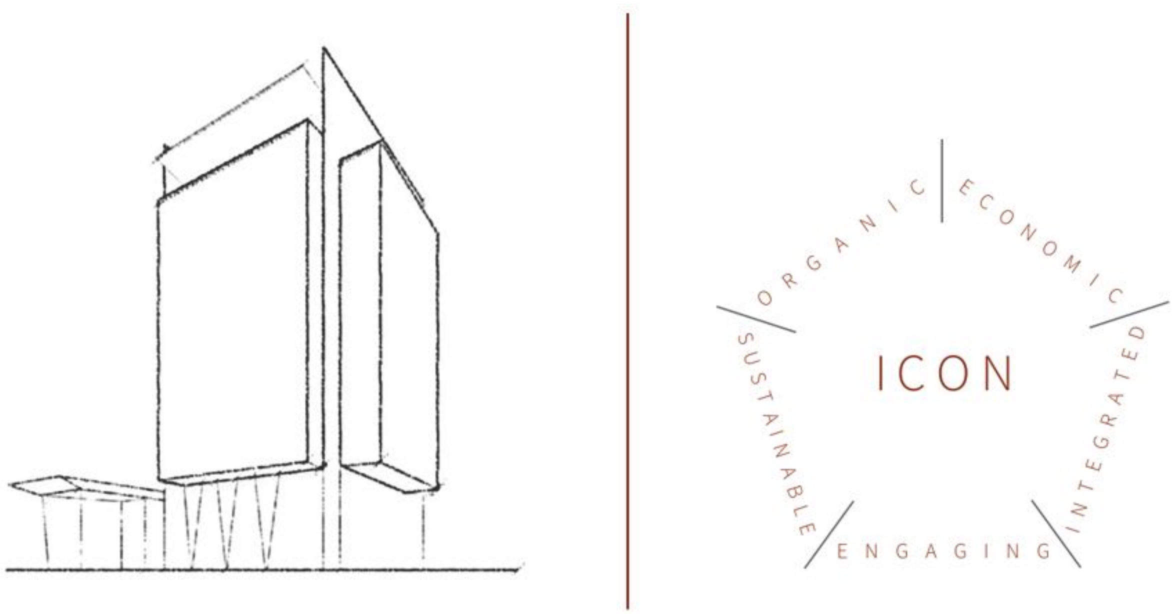
Structural Systems Narrative

EXECUTIVE SUMMARY

Design Group 09-2016 is a multi-discipline consulting firm that specializes in structural, mechanical, and electrical designs. The design team utilizes the latest and most innovative technologies and techniques to provide their clients with efficient buildings that serve as icons of the sustainable design ideology.

Design Group 09-2016 has created the following design development document to outline the design goals and engineering systems for the multi-use 888 Boylston Street project in Boston, Massachusetts. 888 Boylston Street rises from a two-story below-ground parking structure to a three-story retail space capped by a 14-story office space. 888 Boylston Street is set to serve as an icon for the City of Boston through both its architecture and the design of its building engineering systems.

The design team employs comprehensive interdisciplinary collaboration to integrate engineering systems to a standard that is fitting for modern sustainable design. Design Group 09-2016 views a sustainable design as a facility that not only is efficient but also creates as minimal of a footprint on its surrounding environment as possible through the reduction of waste and consumption of resources. This organic relationship between systems creates a building capable of producing significant economic benefits for owners and allows for the full engagement of employees and clients alike.



888 Boylston Street Design Philosophy

COLLABORATION

Collaboration is a fundamental component of integrated design. This idea drove the design team to begin interdisciplinary collaboration at project onset during the development of high-level design goals. Each discipline presented certain goals that would be otherwise unattainable without the direct and early coordination of building systems between the engineering disciplines and the architectural design. In the case of 888 Boylston Street, individual discipline teams participated in brainstorming sessions to generate sustainable ideas that are currently at the forefront of modern architectural design. These sessions led to an abundance of ideas that were closely aligned to the team's core design philosophy of creating a pioneering icon of modern sustainable design within the heart of Boston, Massachusetts. These goals required collaboration between structural, mechanical, and electrical design teams to be realized at their full potential. For example, the implementation of an exposed structural ceiling required specific types of both mechanical and structural systems. Further coordination was essential to ensure these two engineering systems integrated effectively into the daylighting strategies required by the lighting design team to further boost worker engagement and productivity.

PEER REVIEW

With the complex engineering systems required to fulfill the goal of designing 888 Boylston Street as a low-impact, sustainable facility, came a need for thorough review of all design decisions. The design team developed and implemented a multi-faceted review process in which all design documents were reviewed first by another member of the Design Group 09-2016 team, and secondly by a design engineer at a partner professional firm. To ensure a comprehensive interdisciplinary analysis, the in-house review of each discipline's document was performed by a member of a different discipline, while the industry review was performed by a professional engineer of the same discipline as the document being reviewed.

STRUCTURAL SYSTEMS OVERVIEW

The site and structure of 888 Boylston Street presents several major design challenges, many of which require specialized structural systems. The existing site houses a smaller below-ground parking garage that extends over the entire site beneath a plaza. The site is constrained on the west by a nine story building, the east by the Prudential Center Entryway with interior storefronts, the north by Boylston Street, and the south by the Interstate 90 Turnpike and fan room beneath the Prudential Center food hall. Structural integration with these surrounding buildings and structures require specially designed structural systems that will be discussed in detail within this narrative.

The new building at 888 Boylston Street includes a below-ground, two story, cast-in-place concrete parking garage that is connected to the buildings to the west. The superstructure is 17 stories capped with a mechanical penthouse of mixed retail and office occupancy constructed of typical composite beams to steel columns, with a reinforced concrete shear wall core surrounding the central elevator shafts as the lateral load resisting system. The building is supported on drilled shafts that are socketed into bedrock. The highlight of the structural system is a full story high belt truss located on Level 04 that cantilevers 14 stories of office floors 60' over the Interstate 90 tunnel. Figure S.1 shows a section through the building and the location of the interstate tunnel with respect to the rest of 888 Boylston Street.

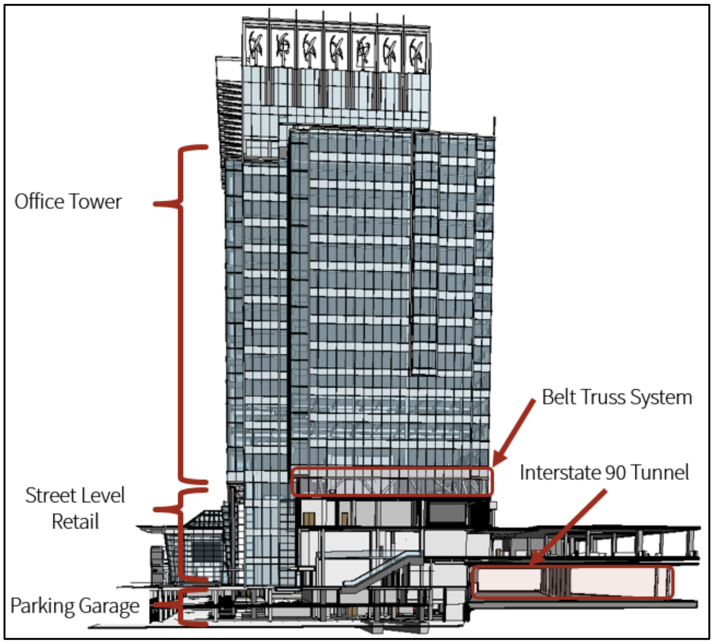


Figure S.1: Structural Overview

FOUNDATION SYSTEM

The 888 Boylston Street site is located less than a half mile from the Charles River Basin and less than two miles from the Boston Main Channel. Through research on the history of the area, it was found that the site is on reclaimed land built up with fill over a thick marine clay layer. Marine clay consolidates under heavy, sustained loads, and as a result, all of the foundations for the larger surrounding structures, such as the Prudential Center, bore through the thick marine clay layer and socket the foundation shafts into bedrock at approximately 150' below Boston City Datum. The provided geotechnical report from Haley & Aldrich, Inc. (May 29th, 2014) recommends a similar system as the Prudential Center: 4'Ø to 8'Ø drilled shafts socketed into bedrock. Considering the magnitude of the loads for the structure and the poor soil conditions, the structural design team agreed with the recommendation and proceeded with the design.

Groundwater Consideration

The high groundwater table at the site of 888 Boylston Street changes the typical design and construction of a deep foundation system. In order to keep the site from filling with water and to allow the contractor to use the required equipment without concern of the site conditions, the structural design team decided to retain the existing mat foundation from the existing parking garage and to core through the mat foundation as needed. The drilled shafts are to be constructed with wet construction methods utilizing slurry to keep the excavations open and a closed or plugged gravity tremie to protect the wet concrete. The drilled shafts are connected to the mat foundation using dowels to create a shear connection to support the mat foundation and to reduce the effects of differential settlement. See Drawing DS.1 for a typical detail.

Design Methodology

Due to the high cost of the required foundation system, the design team started the foundation design with an RSMeans cost estimate to quantify the cost differences between sizes of drilled shafts and auger cast piles. It was found in Boston that a single typical 4'Ø drilled shaft, such as DS1.5 (see Table S.1), would cost around $46,500 and a single typical 6'Ø drilled shaft would cost around $90,500, almost twice as much. Therefore, the most cost effective design approach was determined to be using the 4'Ø drilled shafts to support the main tower columns with the highest loads as recommended and 16"Ø auger cast

Drilled Shaft Types				
	DS1.5	DS2.5	DS3.5	DS4.0
Allowable Capacity	1,500 K	2,500 K	3,500 K	4,000 K
Diameter	4'	4'	4'	4'
Depth of Bedrock Socket	6'	8'	10'	12'
Area of Reinforcement	18 in^2	18 in^2	18 in^2	18 in^2

Table S.1: Drilled Shaft Types

piles for the smaller columns that only support the parking garage and plaza. Four sizes of drilled shafts are used for the project. Their capacities and dimensions are shown in Table S.1. The drilled shafts are adequately designed for axial loads. The steel reinforcement is 1% of the area of the drilled shafts as required by ACI318-11. The geotechnical report requires that half of the drilled shaft capacity comes from side friction in bedrock, hence the depth of the bedrock socket. The drilled shaft layout for the tower columns is shown on Drawing DS.1.

Existing Mat Foundation Considerations

As previously stated, it was the structural design team's intent to retain the existing mat foundation from the existing parking garage and to reuse it for the base level of the new building. Besides the practical benefit of keeping the groundwater under control for the contractor, this design decision saves energy and reduces the amount of waste generated by the demolition of the existing parking garage and reduces the amount of required new material for a new mat foundation for the new building which resulted in a more sustainable overall design. Even with the existing mat foundation, the mechanical design team can install a geothermal system beneath the site by coring 6"Ø holes through the mat foundation and run the connecting pipes through the new 4" topping slab to harness the thermal mass of the ground to create a more sustainable design. For more information see the *Mechanical Systems Narrative*.

In a push to reduce the number of deep foundation elements and mitigate cost, the mat foundation was checked to see if it could support the smaller parking garage columns and distribute that load to the drilled shafts. Unfortunately, there was limited information provided on the existing mat foundation, so it was conservatively assumed the mat foundation was 42" thick and reinforced with a minimal amount of steel reinforcing. With these assumptions, it was found that the mat foundation does not have the required negative moment capacity to support the majority of the smaller columns. However if the existing mat foundation design was confirmed through the existing plans or ground-penetrating radar, the number of auger cast piles could be further reduced.

GRAVITY SYSTEMS

Superstructure Framing Design

The superstructure of 888 Boylston Street consists of 17 stories of office and retail capped with a mechanical penthouse and is constructed of a typical composite beam system to W14 columns.

The RISA Product Suite was the primary software used to aid in the design of the gravity floor framing system and columns and lateral system. It was important to use a software suite that could design full floor cantilevers and trussed transfer girders. RISA Technologies generously provided a temporary license for the required software to be used for this project.

The composite decking is a 3" deck (Vulcraft 3VLI18) with 3.5" of lightweight topping to reach a two hour fire rating and to allow the beams to be spaced farther apart on all superstructure floors. The heavier deck was necessary to simplify the layout of the building. The layout shown in Figure S.2 has a single deck span direction and spaces the beams at a maximum of 13'. More detailed plans are shown on Drawings DS.2 and DS.3.

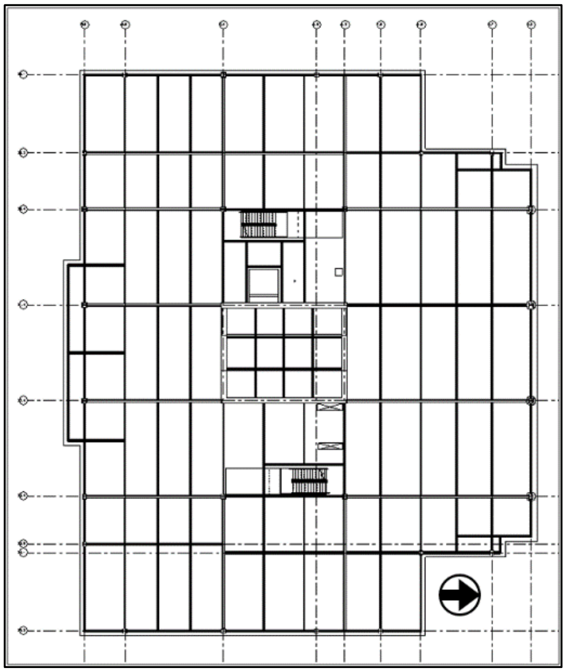


Figure S.2: Typical Office Floor Layout

Since all office floors have an exposed ceiling, it was important to have a consistent structural framing layout. The typical infill beams are W16X26 sections which are supported by girders that are a maximum of 30" deep to keep the maximum structure depth to around 3'. The spandrel beams supporting the exterior curtain wall are W18 sections on the high value north and south façades and W21 sections on the east and west façades. The spandrel beams were designed to deflect less than the limit of L/600 or 3/8" per the recommendations in the AISC Design Guide 3 "Serviceability Design Considerations for Steel Buildings" to avoid issues relating to the movement of the exterior curtain wall.

The exposed ceiling provided design challenges that required interdisciplinary collaboration. Web openings in the composite steel girders were coordinated with the mechanical design team. Floor box and poke through locations were coordinated with the electrical design team, and the depths of the spandrel beams were coordinated with the lighting design team for daylight modeling purposes. The integration required for an exposed ceiling is discussed in more detail in the *Building Integration Narrative*.

Floor vibration was checked by RISAFloor outputs and confirmed by hand calculations using methods from AISC Design Guide 11 "Floor Vibrations Due to Human Activity". It was found that all areas supporting the office spaces experience an acceleration less than 0.5g which is the recommended limit.

Web openings in the composite steel girders were checked by hand calculations using methods from AISC Design Guide 2 "Design of Steel and Composite Beams with Web Openings". It was found that the 12" diameter penetrations required by the mechanical design team in the web of the girders would not require additional reinforcement. Constant coordination with the mechanical design team helped to reduce the number of penetrations.

The camber, number of studs, and column/beam sizes were found with RISAFloor using the loads listed in Appendix SS.1. A typical 30' by 60' office bay was checked by hand calculations to confirm computer outputs. This is shown in Appendix SS.3.

The coordination of the dimensions, locations, and weights of mechanical and electrical equipment across the building was a challenge. The fully redundant mechanical and electrical systems required more equipment than is typical for an office building, so detailed documentation was required. A coordination table was created by the mechanical design team to share key information about the equipment dimensions, weights, and locations.

These design goals, methods, and practices were continued though the design of floors 2 to 18 including the retail, office lobby, and food hall spaces.

Columns and Column Grids

The column grid has been modified to simplify the floor framing plans and the load path. See Figure S.3 for the typical office floor column grid and shear wall locations. The main changes include the addition of a column to the south wall to align the North-South oriented girders on the north side and south side of the building and the general alignment of several columns across the plan.

Other changes were proposed such as adding columns to the corners and further simplifying the layout, but many of the proposed locations did not work practically with the parking garage or the surrounding existing buildings. The structural design team also sought to maintain the original architectural philosophy with the open floor plans and the open cantilevered corners.

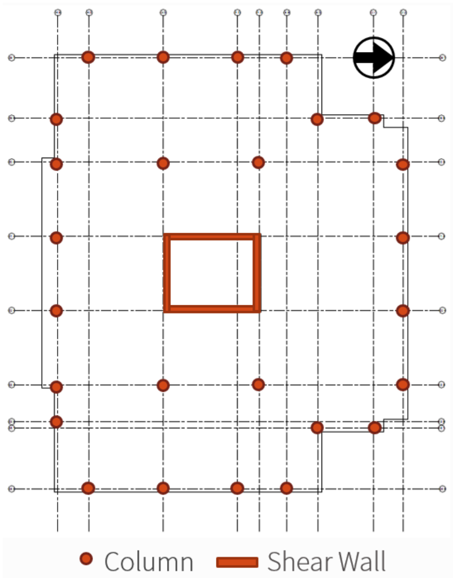


Figure S.3: Column and Shear Wall Locations

In order to reduce weight and labor costs, all of the main tower columns are spliced at the same elevations throughout the entire structure. The columns are first spliced at street level as they change from cast-in-place concrete to steel wide flange sections and are spliced at every 3 stories thereafter. All columns are W14 sections to maintain consistent column sizes across the structure.

Justification of Composite Steel Design

After a preliminary analysis of the structure, the design team decided to proceed with a typical composite beam system. This decision was based on the factors discussed below.

Adding weight to the structure drastically increases the size and cost of the foundation system and increases the complexity of the required cantilever over Interstate 90. A larger foundation system could also interfere with the adjacent structures which would also increase costs. A concrete framing system was found to be approximately twice the weight of a steel framing system, so the design team moved forward with a steel design.

Composite steel beam systems have the advantage of utilizing the slab to transfer some of the flexural compression force. This allows for a shallower and lighter structure than a simple steel beam framing system, and reduces costs by allowing a smaller foundation system and reducing the interference with the surrounding structures.

A study comparing a typical bay of a composite steel framing system, post-tensioned slab system, and voided slab system is shown in Appendix SS.4.

Substructure Framing Design

The structural design team decided to utilize a cast-in-place concrete framing system for the parking garage mezzanine framing and street level framing. Structural concrete is typical for parking garage construction because it is easy to protect from the elements, connect to the pile and grade beam foundations, and connect to the retaining walls around the exterior of the underground garage. The underground parking garage of the building to the east which connects below the ground to the parking garage of 888 Boylston Street is also constructed of concrete.

The maximum depth of the concrete structure is 24” to allow for the minimum clear depth of 7’ as required by IBC 2009 for a passenger vehicle parking garage. The column layout for the parking garage adds intermediate columns into the 60’ spans to create mostly square bays with a maximum span of around 30’. Infill beams are aligned in a single direction to reduce framing costs.

The initial design places cast-in-place concrete beams at 10’ on center with a 6” concrete deck reinforced by #5 bars at 6” on center. See Appendix SS.2 for representative RISAFloor framing layouts.

LATERAL SYSTEM DESIGN

Wind Load Consideration

A main goal for this project was to provide resiliency with respect to local environment considerations. The site of 888 Boylston Street is located near the Atlantic Ocean and is susceptible to hurricanes and high wind situations. In order to adequately design for these scenarios, the typical ASCE 7-05 wind load of 105 miles per hour was increased to the 100 year mean recurrence interval wind speed of 112 miles per hour to design the lateral system for strength. The increased wind speed increases the wind loads on the structure by around 15% to account for a wind speed that has a 64% chance to occur in the next 100 years. The site is not located in a wind-borne debris region.

To further aid in the resistance of the wind loads, the overall structural height of the building was lowered from 298' to 286' which reduces the applied wind load and the building drift. This design decision effectively removed one story from the building and reduced costs across all disciplines. The change in height saved approximately $1,500,000 in upfront costs according to an RSMeans estimate. The structural height change was the result of reducing the typical office floor to floor height from 14' to 13'. This required coordination across disciplines and was a direct result of having an exposed ceiling. More information about the reduction in building height can be found in the *Building Integration Narrative*.

Seismic Load Consideration

The seismic spectral response coefficients were given by the Massachusetts Building Code 8th Edition, and with these coefficients, the building was considered to be in Seismic Category B and had minimal restrictions. Due to the low seismic spectral response coefficients and the now increased, high coastal wind speed, the seismic loads had a low chance of controlling the design, so all preliminary lateral force resisting system calculations were performed using wind loads. However, the final design of the reinforced concrete shear wall core does include applicable seismic loads.

Concrete Core Design

After a preliminary analysis, the structural design team found that the original reinforced concrete shear wall core (30' by 38') would be adequate to resist the lateral loads that would be applied to the structure. A concrete core is typical for buildings of this size and type, matches the architecture, and keeps the lateral loads in the center of the site away from the surrounding structures. For these reasons, the structural design team did not pursue other options.

Concrete Core Comparison			
	Given	First Iteration	Final Iteration
Height	298'	286'	286'
Concrete	4 KSI	4 KSI	6 KSI
Service Shear	2650 K	2500 K	2500 K
% Difference	-	6%	6%
Service Moment	505,000 K*FT	465,000 K*FT	465,000 K*FT
% Difference	-	8%	8%
Deflection	8.25"	6.25"	5.0"
% Difference	-	24%	39%

Table S.2: Concrete Core Comparison

Two changes were made to the original lateral system to reduce the wind load effects and story drift to produce a more resilient lateral system. The first change was the floor to floor height of the typical office spaces dropped from 14' to 13'. This resulted in a 12' reduction for the structure and a lower load for the lateral system. Next through a quick computer model check on the core, it was found that 6,000 psi concrete had significant benefits for the design of the core with respect to shear and moment resistance. The hand calculation results for the effects of the wind loading on the concrete core with these two changes are shown in Table S.2 and Figure S.4. The spreadsheet used to make this graph is shown in Appendix SS.5.

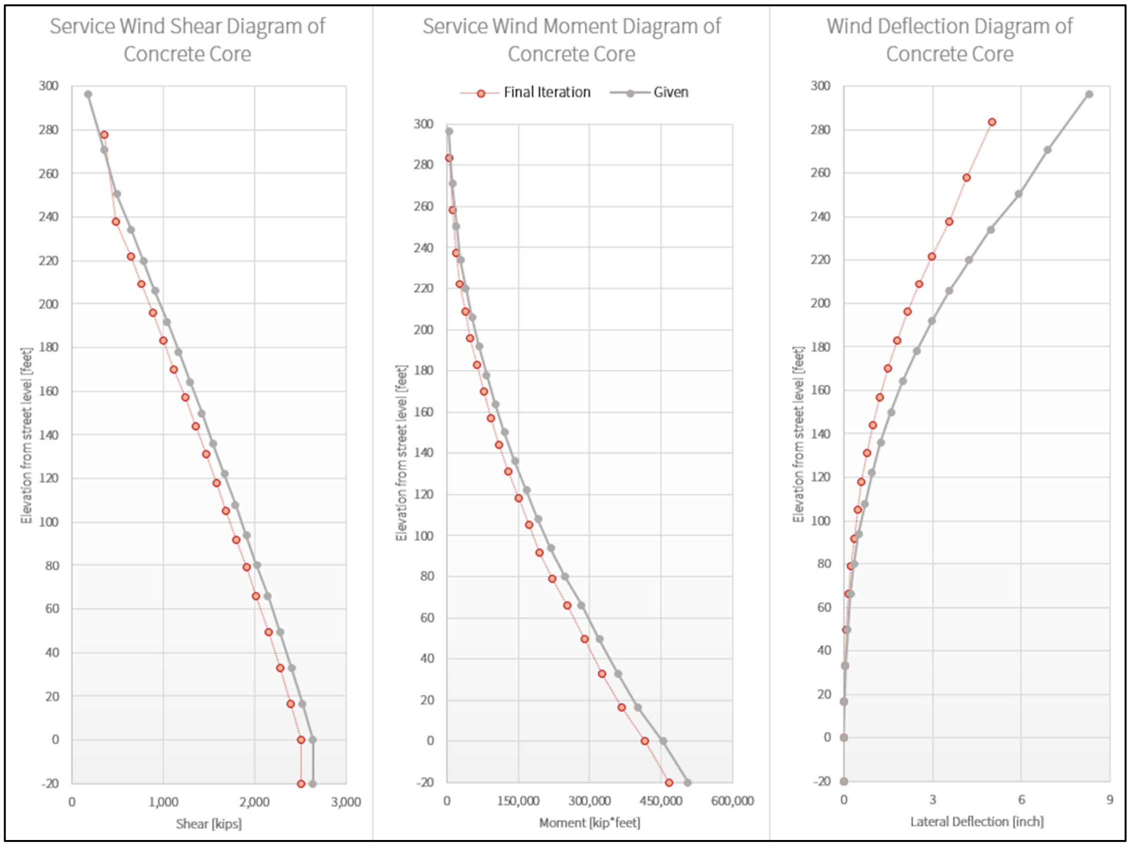


Figure S.4: Graphical Comparison of Concrete Core Iterations

The lateral design of the structure was aided by the utilization of RISA-3D. The integration with RISAFloor allows for a concrete core design to be checked for both the lateral and gravity loading simultaneously. After a thorough analysis including seismic and wind load combinations, it was found that a 6,000 psi concrete core that was 30" thick from the base to Level 05 and 20" thick from Level 05 to the top would be adequate with #11 vertical bars and #8 horizontal bars for the 30" thick walls and with #8 vertical bars and #6 horizontal bars for the 20" thick walls spaced as required from 4" to 18". The lateral loading used for the RISA-3D model is shown in Appendix SS.6.

Wall Panel Reactions				
Wall Panel	Factored Axial		Factored In-Plane Shear	
	Min	Max	Min	Max
WP1	-6,100 K	18,700 K	-2,100 K	2,100 K
WP2	-7,100 K	16,800 K	-2,100 K	2,100 K
WP3	-6,400 K	15,900 K	-1,900 K	1,900 K
WP4	-6,400 K	15,500 K	-1,500 K	1,500 K

Table S.3: Reinforced Concrete Core Reactions due to Wind Loading in the Primary Axis

Wind load combinations in the primary axes produced the highest reactions. The maximum and minimum factored wind load effects on the concrete core are shown in Table S.3. The shear wall locations are shown in Figure S.5. The forces found were reasonably close to the forces found in the previous hand calcuations, justifying the outputs.

The maximum factored compressive force from the bending of the core is approximately 19 million pounds which is adequately resisted by the 30" thick, 38' long, 6,000 psi reinforced concrete wall. The maximum factored tensile force is approximately 7.1 million pounds and is resisted by the concrete wall reinforcement of #11 bars at 10" on center in three curtains. The factored shears for Wall Panels 1 and 2 are equal as expected, but the shears in Wall Panels 3 and 4 are not equal. This is due to the effect of the cantilever causing torsion in the concrete core because of the lack of supports along the edge of the diaphragm. The cantilever is located in the southwest corner of the structure and is shown in Figure S.5. The RISA-3D model of the lateral system is shown in Figure S.6.

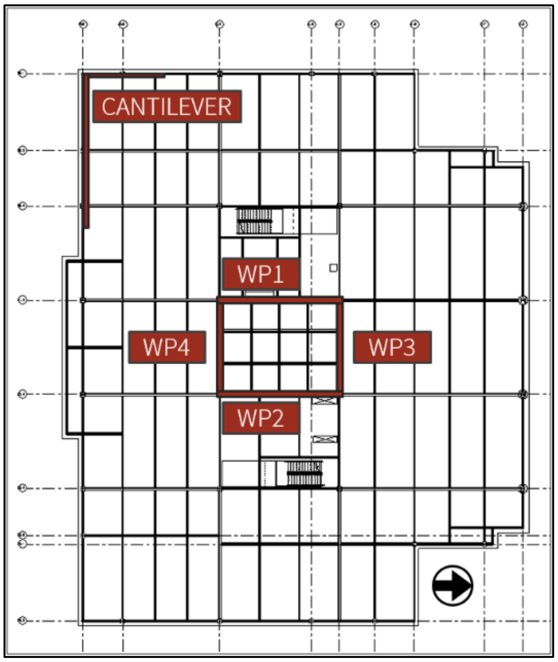


Figure S.6: Location of Shear Walls and Cantilever

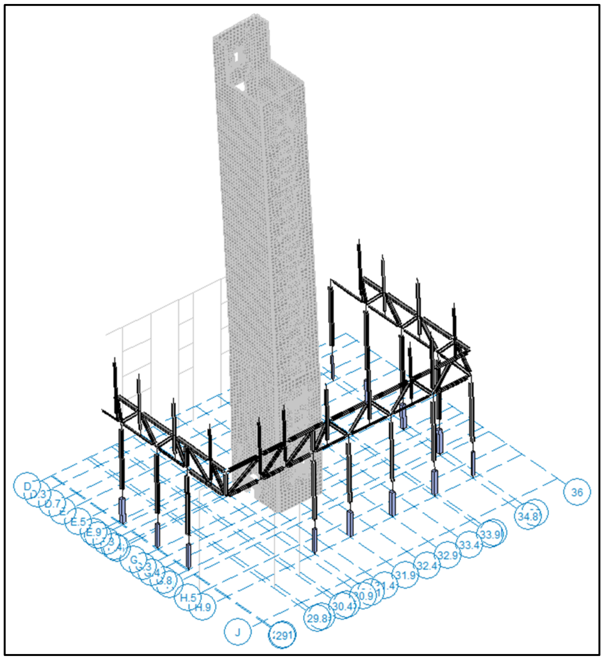


Figure S.5: RISA-3D Model of the Concrete Core and Belt Truss Cantilever

Drift

The aformented concrete core is adequte for a drift limit of L/400, including torsional drift, as recommended by AISC Design Guide 3 "Serviceability Design Considerations for Steel Buildings". The design guide also recommends checking the drift of the structure using a 10 year MRI wind speed or 75% of the 50 year MRI wind speed. However because of the owner's request of "maintaining operation and/or quick restart of a facility of this type during a natural disaster (i.e. hurricane exceeding code minimum values) or other post emergency response situations," the structural design team decided to design for story drift using the 100 year MRI wind speed to ensure that the building and most importantly, cladding, remain structurally sound and tightly sealed in the case of a disaster to aid the in quick restart of the facility. The model story drift of the reinforced concrete shear wall core from the service level 100 year MRI wind speed for the primary axes directions is shown in Appendix SS.7.

SPECIAL AREAS

Storefront

The original storefront of 888 Boylston Street displayed an all glass façade that was supported by three pairs of slanted columns as highlighted in Figure S.7. Alternating with the three pairs of slanted columns are the four tower columns for the 14 stories of office. The transfer of the gravity loads from the tower columns to the storefront pairs of slanted columns proved to be a challenge.

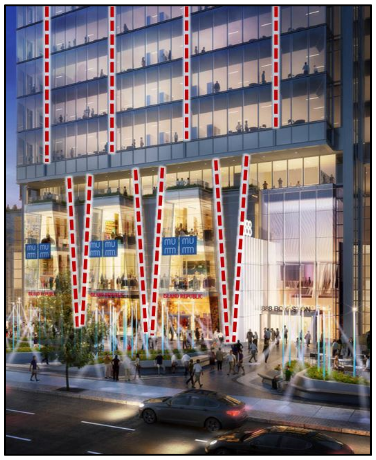


Figure S.7: Architectural Render of Original Storefront (Source: Mikyoung Kim Design)

It was important to the structural design team to keep the original design philosophy of the architect, but a simple modification to geometry was made to match the goals of the entire design team and to simplify the load path. Figure S.8 shows the RISA-3D model of the modified storefront. Both of the outside pairs of slanted columns have changed slopes and termination locations. The bottom locations have been shifted in to make the inside columns vertical, and the top locations of the outside columns have been shifted out to directly pick up the outside tower columns. There are two major benefits of this design. First, the new arrangement organically matches the architecture and points up to the new sky gardens that were added to the front of the building. More information on the sky gardens will be presented in the next section as well as in the *Building Integration Narrative*. Second, the massive cantilevered plate girders that would have been required to pick up the tower columns outside of the pairs of slanted columns were no longer required.

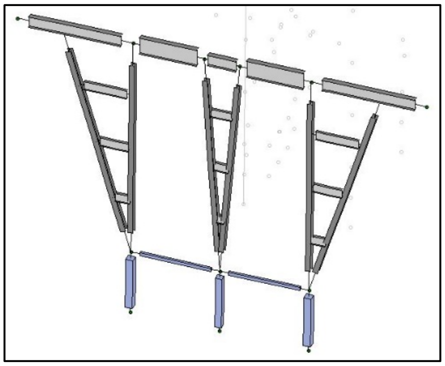


Figure S.8: Modified Storefront Framing

The two exterior columns are W14X605 sections and the rest are W14X500 or W14X455 sections. All columns are controlled by strong axis buckling over the length of the entire column height and carry a factored load of at least two million pounds each. The beam that runs across the top is designed as a continuous W36X441 to simplify the connections and to better transfer the tension through the storefront members. The W36X441 beam is reinforced with a WT20X296.5 section at the two column transfer locations. See the elevation and details on Drawing DS.5 for more information. The horizontal members brace the weak axis of the columns and pick up a 60' girder that spans back into the building. The horizontal braces also add lateral stability by connecting the system back to the concrete core. See Appendix SS.8 for all sizes and the code check of the system.

Sky Gardens

The original plans detailed a possible sky garden location on the south side of the office spaces that was left as an option for the tenant. The lighting design team took it upon themselves to perform a daylighting study to look into other possible locations around the exterior of the building. One of the best locations was on the north side of the building as shown in Figure S.9. Through discussion with the entire design team and consideration of our overarching design team goals of designing sustainable, organic, and engaging architecture and building systems, the team decided to proceed with the design. More information is provided in the *Building Integration Narrative*.

The sky gardens are two stories tall with a terrace on the first story and a mezzanine on the second. The framing plan is similar on both stories, only the spandrel is removed on the mezzanine levels. Drawings DS.2 and DS.3 show the two different framing layouts. The newly exposed columns and beams are clad with fireproof composite aluminum panels, matching the storefront columns below.

Figure S.9: Sky Garden 3D View

Belt Truss System on Level 04

Because of the difference in column grids between the tower of 888 Boylston Street to the surrounding structures, and because of the interference of Interstate 90 and its fan room, a massive belt truss lining three quarters of the exterior of the building is required. The east elevation truss was originally located on the story below, but the structural design team simplified the design and raised the transfer truss to be on the same story as the cantilever. See Figure S.10 for a visual of the RISA-3D model of the modified truss structure.

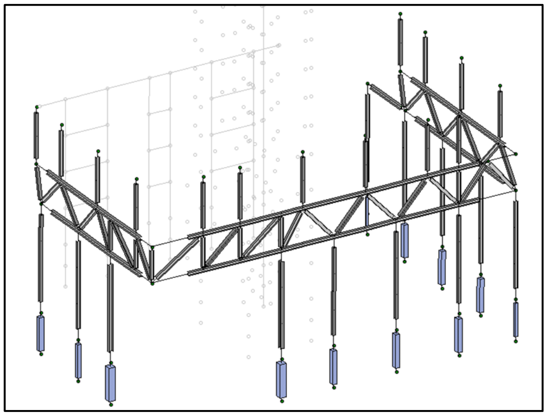


Figure S.10: RISA-3D Model of Truss System

There are two purposes for the belt truss design. The first is to transfer the loads from the tower columns to the alternating parking garage columns below as shown in the east elevation in Figure S.12. The second purpose is to create a truss that is able to cantilever over the interstate and fan room. See the west and south elevations shown in Figures S.11 and S.13. The alternating column locations actually aid in the design of a stiff truss that is capable of the cantilevering 14 stories of office floors 60’ over an interstate.

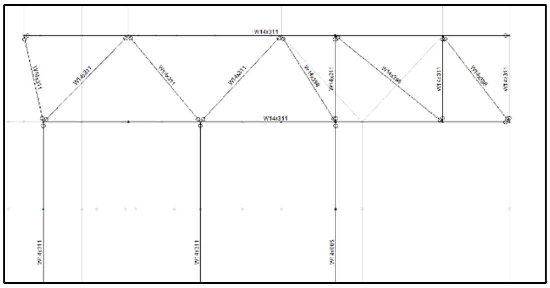


Figure S.11: West Elevation

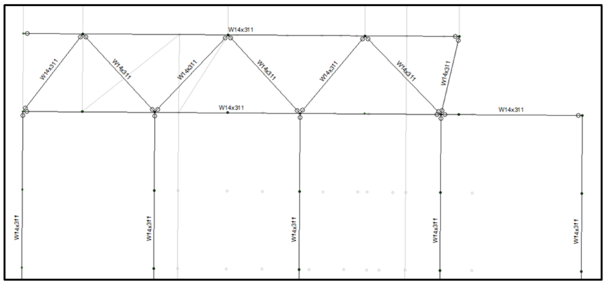


Figure S.12: East Elevation

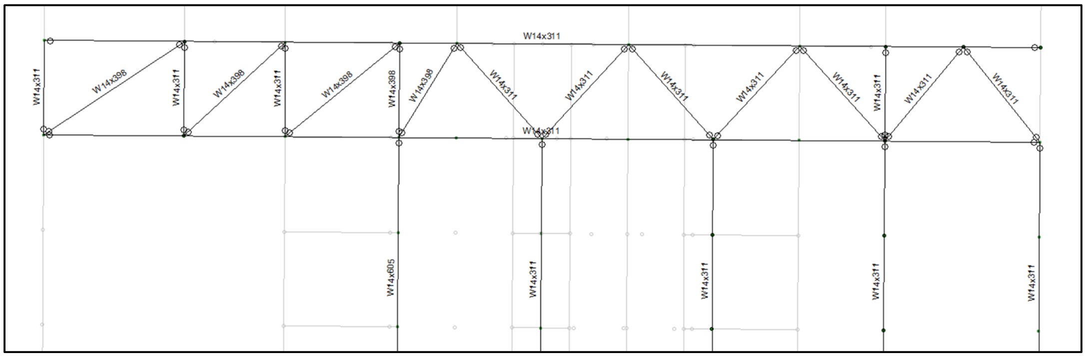


Figure S.13: South Elevation

Efficient truss designs were determined through iterative checks and attempts to create a uniform truss. It was found that a "Pratt" style truss worked the best and created a uniform layout through the cantilever. A drawback to the "Pratt" style of truss was the vertical members in the truss had to be increased in size to account for the extra compressive force added by the truss geometry. The member sizes in the truss are large and sized conservatively. It was the intent of the design team to create a consistent truss all the way around the floor. The code check for the Level 04 Belt Truss System is shown in Appendix SS.9. More detailed elevations are shown on Drawing DS.6.

The truss has been designed to be constructed as easily as possible to save on labor costs. Both the top and bottom chord are designed as continuous members with the idea that truss sections could be shop fabricated and assembled, and shipped to the site in large units. The truss sections would then be lifted into place and bolted to the cap plates of all of the columns.

Unitized Curtainwall Façade

Due to the high performance criteria required for 888 Boylston Street, a shop fabricated, unitized curtain wall façade is used for this project. A unitized curtainwall façade is a prefabricated unit comprised of glazing, mullions, and connections that are shipped to the site as a single unit and are typically fastened to the structure with proprietary and specially engineered connections. Unitized curtainwall façade systems are utilized on larger projects because of the higher build quality and reduced onsite labor costs when compared to a typical stick-built curtainwall. They are also installed in approximately a third of the time, saving budget and schedule.

These systems are typically used on office buildings such as 888 Boylston Street and can be designed to resist the high winds experienced in a coastal region. Since the wind speed given by the Massachusetts Building Code is 105 MPH, the project is not considered to be in a wind-borne debris region which reduces the cost of the curtain wall system. The system is supported on spandrel beams on every floor which have a total dead load deflection limit of L/600 or 3/8".

INTEGRATION WITH AND IMPACT ON SURROUNDING STRUCTURES AND PUBLIC WAYS

Community Driven Construction Methods

The building at 888 Boylston Street fills in one of the last undeveloped areas of the Back Bay neighborhood. The surrounding community is a bustling commercial and residential hub for the city. For this structure to organically fill the physical void of the site, it must be built in a responsible manner to allow for the community to continue with minimal interruptions. The design team has proposed several measures to allow this to happen.

First, the construction will abide by city rules limiting the amount of excessive noise, dust, traffic, and vibration and the times during the day when construction can occur. For Boston, these times are 7:00 AM to 6:00 PM during the week. Moreover, construction worker parking and transportation is a concern with the minimal surface area for parking nearby. Programs will be put in place to encourage workers to either use the substantial public transportation in the area or car pool with at least three other workers to help minimize the impact on the quality of life of the neighbors. Finally, a community liaison will be appointed to inform the public of upcoming traffic issues or other similar annoyances. The liaison will be available at all times to field public comments or complaints.

The pedestrian sidewalk to the north of the site will remain open throughout the construction of the project. A chain link fence with plastic slats with warning signage will be constructed to protect and separate the pedestrians from the construction site. With the site surrounded by other buildings on three sides, the entry for vehicles onto the site has to cross the busy pedestrian sidewalk. A stop sign for the construction vehicles should solve the traffic problem for the majority of the time, but a crossing guard could be utilized during peak pedestrian traffic hours. However, it should be a priority of the contractor to avoid deliveries and traffic to and from the site during peak vehicular and pedestrian traffic hours.

Construction Area and Sequencing

The site of 888 Boylston Street has a large plaza to the north of the building as shown in Figure S.14. There is room to set up a large tower crane in the center of the plaza and still have an area for storage and laydown. One concern of the structural design team is that the underground parking garage does extend past the building to the street. It is ideal for the existing retaining walls for the existing parking garage to remain in place for the new structure, so the initial laydown area for construction materials is the bottom level of the parking garage, around 19' below street level. This requires the creation of large ramp made of fill, so equipment can drive down to the laydown area.

Structural Systems Narrative

The construction of the structure can proceed typically. Demolition of the existing structure, drilled shaft foundations to concrete core to concrete substructure to steel superstructure, and the parking garage can be finished once the tower crane is finally removed. The demolition of the existing parking garage needs to be carefully controlled in order to reduce noise and dust proliferation. It is the design team's recommendation that the existing parking garage be demolished with excavators using concrete cutter jaws and water spray attachments to reduce the dust. This will allow materials to be easily crushed and sorted, and then, most importantly, recycled.

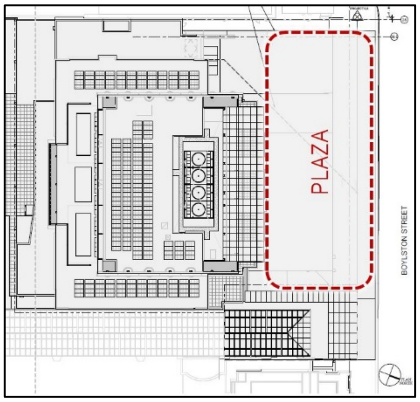


Figure S.14: Site Layout

Building Expansion Joints

Building expansion joints are provided at all locations where 888 Boylston Street "connects" with adjacent structures. This includes the area on and around the interstate fan room, open areas that connect to the food hall and Prudential Center entry, and the other existing structures in the parking garage. Since we do not have the methods to evaluate the other structures' foundation system for long-term deflections, the structural design team decided to avoid the problem by disconnecting the structure from the existing surroundings. This also helps other surrounding buildings limit the amount of construction in their spaces to help them save time and budget.

SUSTANABLE DESIGN AND CONSTRUCTION

Sustainable Construction Methodology

With the Public Sustainability Knowledge initiative discussed in the *Building Integration Narrative*, it was important to construct 888 Boylston Street with renewable and responsible methods starting with the demolition of the existing parking garage. As discussed previously, tearing apart the parking garage with excavators with jaws allows the concrete rubble, rebar, and other materials to be sorted and recycled. The concrete rubble can be crushed and used as filler or aggregate for new concrete on this project or others in the area. The rebar can be sent back to a steel mill to be recycled. Projects that have been demolished using similar methods have experienced recycling rates over 90%. For the construction of the new building, the structural design team recommends a thorough recycling and construction waste management plan that reduces the amount of waste produced by the project to under 2.5 pounds of construction waste per square foot to help mitigate the volume of material that is sent to a landfill.

Sustainable Design Methodology

The building of 888 Boylston Street was designed to be an icon of sustainability, both by being a leader in sustainable design and by teaching the public about responsible practices. The reuse of the mat foundation, the sky gardens, the reduced floor to floor height, and the Sawtooth Façade (see the *Building Integration Narrative* and Drawing DS.7 for a structural section) are all examples of sustainable improvements involving the structural design team. The reuse of the existing mat foundation saves energy, reduces demolition waste, and saves material for the new structure. The sky gardens improve the daylighting for the office floors and the lifestyle of the office employees. By reducing the floor to floor height, less material was used in construction and the volume of the building was reduced, reducing the energy required to heat and cool the building. The slanted south façade acts as an inherent shade, provides significant space for solar panels, and showcases the sustainable design of the structure for all occupants.

The structure of 888 Boylston Street is constructed of structural steel in part for its sustainable benefits such as being a great regional material from the Northeast, and consisting of an average of 93.3% recycled material. Structural steel also has the added benefit of being cheap and simple to reinforce or modify for future tenants. At the end of 888 Boylston Street's useful life, structural steel is easy to reuse or recycle.

If all of the design team's sustainability recommendations are followed, the project will have no issues achieving a LEED Platinum award. See the *Building Integration Narrative* for more information.

RESILIENCY WITH RESPECT TO LOCAL ENVIRONMENTAL CONDITIONS

Located on the north Atlantic Coast, 888 Boylston Street will always be threatened by high winds and hurricanes. The community focus of this project requires that the building be able to withstand and be reoccupied immediately after a disastrous event. To reach these goals, several structural design changes were made. The first was the wind speed used to size the reinforced concrete shear wall core was increased to a 100 year mean recurrence interval in order to increase the period of time between ultimate wind speed events and to decrease the likelihood of a damaging event. Second, the reduction of the building height reduces the amount of wind load that is applied to the building. Third, the reinforced concrete core was checked for drift using an increased wind speed to ensure the building and cladding remain structurally sound and tightly sealed in the disastrous event of high winds or hurricanes. And finally, the use of a unitized curtain wall system produces a higher quality building envelope that better resists hurricane force winds and aid in the quick restart of the facility.

CONCLUSION

The structural design team, in conjunction with the mechanical and electrical design teams, has worked tirelessly to produce an integrated and sustainable design for 888 Boylston Street. The result is an organic meshing of structural, mechanical, and electrical systems to produce a body that is both wildly efficient and economically feasible while promoting the engagement of its occupants in the pursuits of office life and the learning of sustainable practices. From the structural modification of the storefront columns and the belt truss system on Level 04 to the interdisciplinary integration on the sky gardens and façade, the design team has sought out only the most aesthetic and efficient solutions to serve as an Icon of sustainable and modern design for the City of Boston.

Integration | Structural | Mechanical | Electrical

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Mechanical Systems Narrative

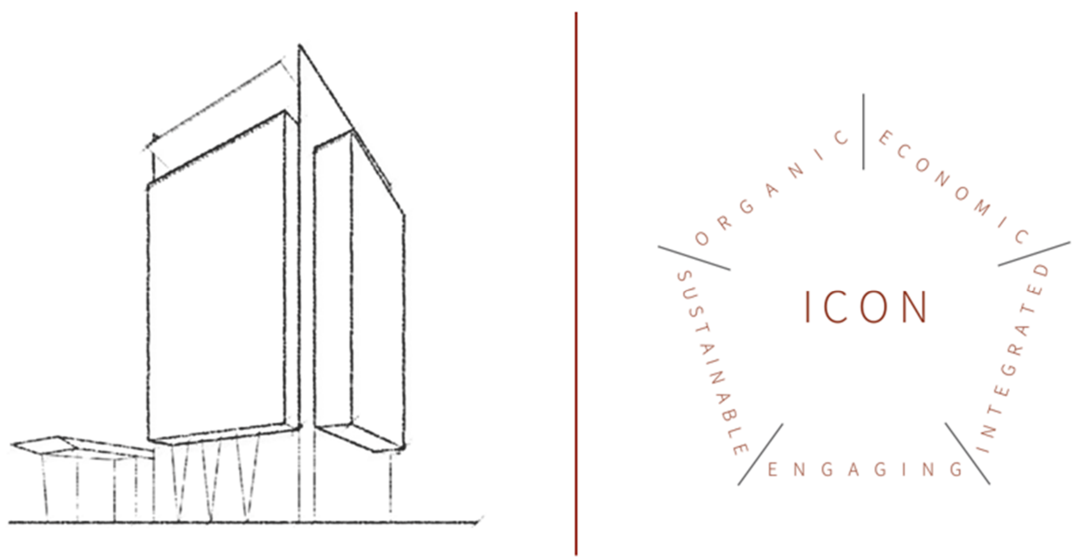
Mechanical Systems Narrative

EXECUTIVE SUMMARY

Design Group 09-2016 is a multi-discipline consulting firm that specializes in structural, mechanical, and electrical designs. The design team utilizes the latest and most innovative technologies and techniques to provide their clients with efficient buildings that serve as icons of the sustainable design ideology.

Design Group 09-2016 has created the following design development document to outline the design goals and engineering systems for the multi-use 888 Boylston Street project in Boston, Massachusetts. 888 Boylston Street rises from a two-story below-ground parking structure to a three-story retail space capped by a 14-story office space. 888 Boylston Street is set to serve as an icon for the City of Boston through both its architecture and the design of its building engineering systems.

The design team employs comprehensive interdisciplinary collaboration to integrate engineering systems to a standard that is fitting for modern sustainable design. Design Group 09-2016 views a sustainable design as a facility that not only is efficient but also creates as minimal of a footprint on its surrounding environment as possible through the reduction of waste and consumption of resources. This organic relationship between systems creates a building capable of producing significant economic benefits for owners and allows for the full engagement of employees and clients alike.



888 Boylston Street Design Philosophy

COLLABORATION

Collaboration is a fundamental component of integrated design. This idea drove the design team to begin interdisciplinary collaboration at project onset during the development of high-level design goals. Each discipline presented certain goals that would be otherwise unattainable without the direct and early coordination of building systems between the engineering disciplines and the architectural design. In the case of 888 Boylston Street, individual discipline teams participated in brainstorming sessions to generate sustainable ideas that are currently at the forefront of modern architectural design. These sessions led to an abundance of ideas that were closely aligned to the team's core design philosophy of creating a pioneering icon of modern sustainable design within the heart of Boston, Massachusetts. These goals required collaboration between structural, mechanical, and electrical design teams to be realized at their full potential. For example, the implementation of an exposed structural ceiling required specific types of both mechanical and structural systems. Further coordination was essential to ensure these two engineering systems integrated effectively into the daylighting strategies required by the lighting design team to further boost worker engagement and productivity.

PEER REVIEW

With the complex engineering systems required to fulfill the goal of designing 888 Boylston Street as a low-impact, sustainable facility, came a need for thorough review of all design decisions. The design team developed and implemented a multi-faceted review process in which all design documents were reviewed first by another member of the Design Group 09-2016 team, and secondly by a design engineer at a partner professional firm. To ensure a comprehensive interdisciplinary analysis, the in-house review of each discipline's document was performed by a member of a different discipline, while the industry review was performed by a professional engineer of the same discipline as the document being reviewed.

OVERVIEW OF SYSTEMS *(AES): Denotes Advanced Engineering System* *(VE): Value Engineering Option Present*

Cooling System Overview

Active chilled beams (ACB) in combination with radiant flooring are specified to satisfy the majority of the building's conditioning and ventilation air distribution needs. Active chilled beams handle the cooling loads of all office floors as well as all internal retail spaces. To prevent condensation in areas adjacent to building openings, alternative air distribution systems are used within lobby and first floor retail areas as discussed below in the *Secondary Systems* section. Through the specification of chilled beams in the majority of internal spaces (which shifts a significant portion of the cooling load to the water within the chilled beam cooling coils), the design team was able to supply the building exclusively with 100% outdoor air units. This maximizes the indoor air quality for occupants by providing a constant flow of fresh air into virtually every space within the building and immediately shows the intent of the design team to create a stimulating and engaging environment for all workers and visitors of 888 Boylston Street.

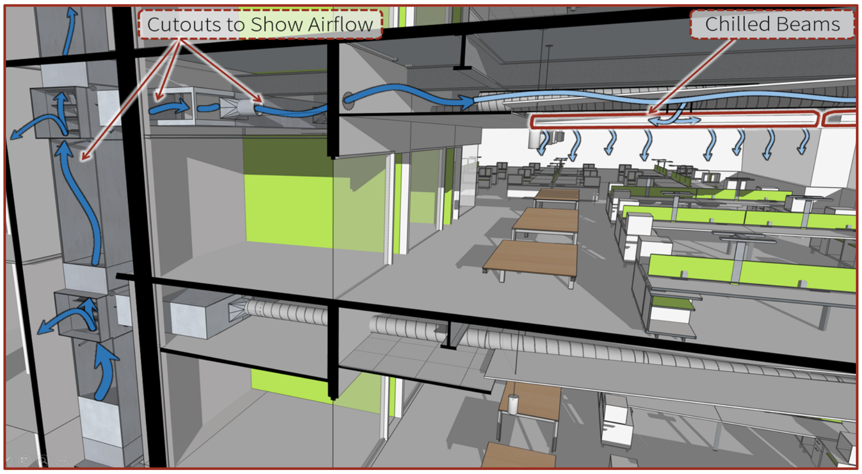


Figure M.1: 888 Boylston Street Mechanical System Section

Four 270-ton heat recovery chillers located within the mechanical penthouse provide 44 °F chilled water for use in the chilled water loop within the building as outlined in Table M.1. Specifically 44 °F water feeds the two air handlers located on the upper level of the mechanical penthouse while 58 °F water feeds the active chilled beams through a mixing system that introduces 63 °F ACB return water into a portion of the 44 °F chilled water supply. This mixing system is explained within the *Primary System* section with full drawings available in *Appendix DM.2*. Heat is rejected through a hybrid geothermal and sea loop system as shown in *Appendix DM.2* and explained in the *Primary System* section below.

CHILLED WATER LOOP DESIGNATION	WATER TEMPERATURE	LOOP FLOW RATE	ΔT
ACTIVE CHILLED BEAM LOOP	58 °F	2,500 GPM	5 °F
AIR HANDLING UNIT LOOP	44 °F	1,060 GPM	12 °F

Table M.1: Chiller Design Criteria

Heating System Overview

To tailor the hot water system to the selected space conditioning systems, two hot water loops were created. One loop serves the radiant floors while the other serves the heating coil within the air handling unit (AHU) that treats the outdoor air used for ventilation. The two hot water loops have a maximum load of 11,000 MBH and are fed by six 2,000 MBH condensing boilers located within the mechanical penthouse. By specifying six boilers, redundancy is added to the heating system. The boilers are run in parallel at low output volumes, increasing system efficiency.

Exhaust System Overview

Office Exhaust

Due to the supply of 100% outdoor air into all office spaces, the building contains a ducted exhaust system that extracts air rather than a typical ducted return air system. In order to maintain positive pressure to prevent the infiltration of humid air (critical for proper active chilled beam function), all spaces are designed with an exhaust flow rate equal to 90% of the supply air flow rate. All office floors are exhausted via fans located within the two penthouse AHUs, and air is sent through an enthalpy wheel to recapture waste heat. In a 100% outdoor air system, the pretreatment of outdoor air is especially critical and large energy savings occur during cold winter months.

Retail Exhaust

Rather than pull retail exhaust air through the entire building simply to be exhausted at roof level, the retail floor exhaust air is removed via exhaust fans located in the mechanical room on the 3rd level. This allows for the reduction in size of exhaust ducts above the third floor and lowers the exhaust static pressure, reducing fan energy requirements.

Garage Exhaust

The two level underground garage creates several challenges, as there is no direct access to street level within the 888 Boylston Street site. Full mechanical ventilation was provided based on occupancy and vehicular motion per IMC 2009 requirements. The variable flow system exhausts at rates shown in Table M.2. In the case of a fire, the system must be able to exhaust at a rate of six air changes per hour. The exhaust system is sized upon either on the area-based rate or smoke exhaust rate (higher value controlling).

GARAGE EXHAUST	AREA (FT^2)	MAX RATE / TOTAL FLOW (CFM/FT^2) / CFM	AC/H	MIN. RATE / TOTAL FLOW (CFM/FT^2) / (CFM)	CFM SIZING (PER 6 AC/H)
Garage Floor #1	28,000	0.75 / 21,000	5.3	0.05 / 1,400	24,000
Mezzanine Park	9,000	0.75 / 6,800	2.5	0.05 / 450	16,000

Table M.2: Garage Exhaust Air

Primary Systems

(AES) Hybrid Geothermal and Sea Loop

(VE) While traditional cooling tower systems are a common low-cost method of cooling system condenser heat rejection, they are consume large amounts of chemically treated water, as they rely on evaporative cooling. The design team turned to geothermal heat rejection methods to dramatically reduce the water consumption of building mechanical systems. However, due to the site footprint restrictions, a geothermal loop could not be sized to meet the full heat rejection needs of the building. Therefore, a hybrid system was designed in which a sea loop (located 1,800 feet away in the Charles River) would function in unison with the geothermal loop (located on site) to reject cooling system heat. Combined, the hybrid loop system is sized to meet 85% of the design day load as defined by Trane Air Conditioning Economics (TRACE) 700. Due to the definition of a design day, sizing to this percentage is sufficient for the vast majority of days within the building. To save cost and add resiliency a supplemental cooling tower was sized to meet the remaining 15% of the design day load. This ensures proper cooling performance on even the most extreme days, and provides increased resiliency in the case that one of the loops needs emergency maintenance. The sizing of the heat rejection system is outlined in Table M.3.

PRIMARY SYSTEMS	PERCENT OF DESIGN DAY LOAD	HEAT REJECTION CAPACITY	DERIVATION OF CAPACITY
GEOTHERMAL LOOP	85%	120 Tons	(AREA LIMITED)
SEA LOOP		820 Tons	0.85 x (1080-120)Tons = 820 Tons
COOLING TOWER	15%	140 Tons	(1080-120-820)Tons = 140 Tons

Table M.3: Hybrid Loop Design Criteria

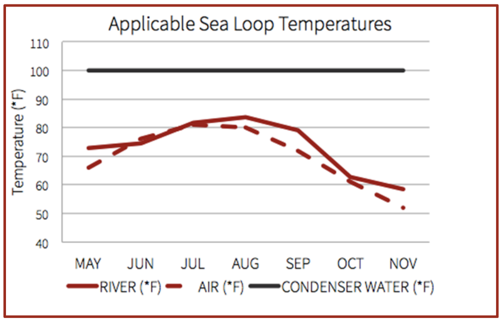


Figure M.2: Sea Loop Temperatures

This hybrid system clearly carries a higher initial cost than a traditional cooling tower system but promises significant payback and utility usage reductions. Since the full heat rejection load is handled by the two loops on all but the most extreme summer days, the mechanical team was able to remove the need for the evaporative cooling tower process and save over 340,000 gallons of waste water per year (per Trane TRACE 700), lowering operating costs and allowing 888 Boylston Street to do its part in reducing cities' reliance on natural resources while generating substantial payback. In the event of a budget decrease, the design team has prepared a value engineering option for this heat rejection system that is described within the *Value Engineering* section later in this document.

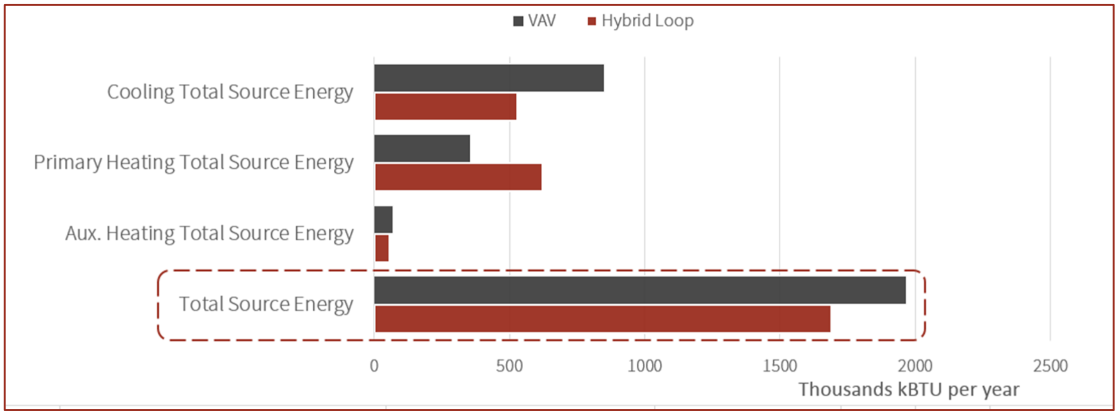


Figure M.3: System Energy Usage Comparison (Trane TRACE 700)

<u>Heat Recovery Chillers</u>

The heat extracted from water during the process of creating chilled water is a significant potential source of heat. To prevent this heat from being wasted directly through the heat rejection equipment, heat recovery chillers are specified with the goal of capturing waterside waste heat. This waste heat within the condenser water is transferred from the four 270-ton chillers via a plate and frame heat exchanger to be used for domestic hot water preheat. This reduces domestic hot water heater energy consumption while also decreasing the load (and subsequently the size) of heat rejection equipment.

<u>Low Temperature Condensing Boilers</u>

As commonplace in modern efficient buildings, a condensing boiler system is used with special attention given to the system water flow to ensure a low temperature return water. As seen in Equation M.1, a low return temperature creates a large ΔT, minimizing the required flow rate through the inverse relationship. Reducing overall flow rate lowers initial costs by allowing for

$$Flow\ rate = \frac{Q}{k \times \Delta T}$$

Equation M.1: Boiler Flow Rate Parameters smaller pipes and pumps and lowers operating costs through smaller pump energy required within the system. A full sample equation is provided in Appendix SM.1.

Air Handling Units (AHU)

The four chillers and six boilers supply conditioned water to the two AHUs located in the mechanical penthouse atop the structure. These AHUs treat the outdoor air used to meet ventilation requirements and cooling loads within the building and are designed with a low-pressure methodology. Ultraviolet (UV) lights are provided on both the cooling coil and drain pan to prevent mold growth and particle buildup, thus increasing indoor air quality and reducing maintenance costs. Due to the large size, weight, and significant electrical requirements of this and other mechanical equipment, a coordination table (Table M.4) was created to provide key data to the structural and electrical design teams saving time and promoting accurate design.

GENERAL			STRUCTURAL		ELECTRICAL				
TYPE	#	LOCATION	WEIGHT (lb.)	L x W x H (in.)	MCA	MOCP	FLA	HP	V/P/H
AHU (WITH SUPPLY)	2	PENTHOUSE	36,000	254 x 182 x 178	-	-	93.1	17.9	480/3/60
FAN (EXHAUST)	4	PENTHOUSE	800	58 x 58 x 69	-	-	-	7.5	480/3/60
CHILLER	4	PENTHOUSE	11,030	152 x 36 x 69	335	400	-	-	480/3/60
BOILER	6	PENTHOUSE	1,560	38 x 29 x 80	-	-	6.2	-	480/3/60
COOLING TOWER	1	PENTHOUSE	2,980	130 x 130 x 90	-	-	7.3	5	480/3/60
PUMP (HOT WATER)	1	PENTHOUSE	400	25 x 12 x 25	-	-	-	10	480/3/60
PUMP (CHILLED WATER)	1	PENTHOUSE	1,000	53 x 25 x 32	-	-	-	40	480/3/60
PUMP (FIRE)	1	GROUND	400	84 x 30 x 21	-	-	-	125	480/3/60
PUMP (DOMESTIC)	1	GROUND	470	42 x 19 x 12	-	-	-	30	480/3/60
PUMP (SEA LOOP)	1	GROUND	4500	87 x 36 x 43	-	-	-	250	480/3/60

Table M.4: Coordination Table

Secondary Systems

Active Chilled Beams

Active chilled beams were specified to satisfy a majority of the building's air distribution and cooling needs. Selected in part for their performance in the *System Selection Matrix* shown in Appendix SM.2, active chilled beams use a combination of conditioned outdoor air and cooling coil to provide cooling within a room. The conditioned outdoor air is supplied at a rate equal to room ventilation requirements, ensuring proper indoor air quality. Because of this, active chilled beams require significantly less airflow versus traditional all-air VAV systems. The remainder of the room's cooling load is fulfilled by the cooling coil within the unit, taking advantage of the high specific heat of water. By reducing duct

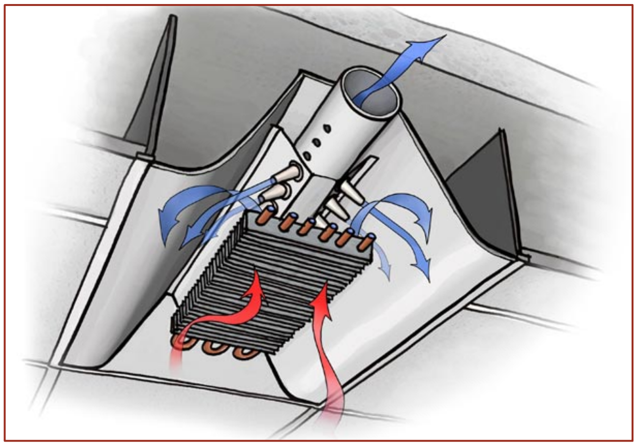


Figure M.4: Active Chilled Beam
(Source: Affiliated Engineers, Inc.)

size, the application of an active chilled beam system reduces the ceiling space required by mechanical systems, enabling the use of an exposed ceiling to help with the goals of the lighting team of creating empty ceiling cavities as further outlined in the *Electrical Systems Narrative,* as well as allowing for the reduction of floor-to-floor heights, as outlined in the *Building Integration Narrative*. The smaller ducts also allow for the creation of a more basic and architecturally pleasing layout of ductwork resulting in fewer beam penetrations, easing the job of the structural design team.

Active chilled beam systems work well in areas with low humidity and relatively low ceilings (less than 16 feet) making the lowered 13 feet ceilings of this project a suitable candidate. Important design conditions include:

- Maintain dry coil conditions ($T_{dp} > T_{coil}$) through higher supply water temperature
- Maintain an unobstructed air path

To satisfy the above design conditions, active chilled beams are used on all office floors (except data rooms), Retail 2, and Retail 3 floors. Additionally, active chilled beams serve the primary retail space on Retail 1, with 100% outdoor air units used in the lobby spaces, as described below.

<u>All-Air Cooling (Condensation-Prone Spaces)</u>
The major drawback to an active chilled beam system is its susceptibility to coil condensation. This caused the design team to choose a different method of cooling within and directly adjacent to the Lobby areas on the Retail 1 and Retail 2 floors, including the Food Hall entrance. This is especially important in these areas, as they contain numerous doors and significant amounts of infiltration air, which has the potential to be humid. The two AHUs within the building feed 100% outdoor air to be used for cooling. While treating this outdoor air is a more energy intensive process than using mixed air, the option comes with several benefits. First, by using outdoor air, the design team eliminates the need to specify traditional air handlers for such a small group of spaces. The second benefit is the increased indoor air quality of the space as a result of how the amount of ventilation air supplied to the space far exceeds code minimum. Any person entering the lobby spaces is greeted with a burst of cool and clean outdoor air, despite being inside of the structure. To reduce the amount of air needed within these spaces, supply air is injected at floor level, and exhausted at the ceiling. This allows for an increased zone air distribution effectiveness, decreasing ventilation air requirements by 20%.

<u>Radiant Floor</u>
With an active chilled beam system serving a majority of the building's cooling needs, the mechanical team proceeded with the design of a water-based system to satisfy the heating needs of the building. While the *System Selection Matrix* (shown in Appendix SM.2) outlines the system's overall performance, specific traits of the radiant heating system make it a clear choice for 888 Boylston Street. By harnessing the high heat capacity of water (as outlined above in the *Active Chilled Beams* section), the design team was able to further reduce the amount of ductwork within the building, thus reducing architectural requirements and opening up space for the Stack Effect Ventilation System outlined below. By the nature of an in-floor heating

system, uniform heat is provided across the entirety of the floor where it can then slowly rise throughout the space. This method of heating is more effective than ceiling supply systems as it creates well-mixed air and enables the large amount of glazing on 888 Boylston Street to be washed with hot air thus eliminating concerns for wintertime condensation. While the radiant system is more expensive than a simple all-air heating system, the space saving benefits and increased efficiencies play a vital role in the pursuit of a sustainable design.

Due to the radiant floor system's location within the slab, careful coordination was required with the structural team to maintain slab integrity. Additionally, detailed coordination with the electrical team was required in order to implement the in-slab poke-through electrical boxes specified within the *Building Integration Narrative*. While the three-dimensional coordination added complexity, the consistent level and methods of integration developed across the entire design team ultimately led to a more energy efficient, user-friendly, and iconic design.

(AES) Water Collection and Power Generation

With the goal of meeting the more stringent guidelines of ASHRAE Standard 189.1, the collection of rainwater and coil condensate becomes more than just a sustainable idea; it becomes a necessity. ASHRAE Standard 189.1 Section 6.4.3 requires the water feature - which serves as the focal point of the Plaza - to "be supplied either by alternate on-site sources of water or by municipally reclaimed water delivered by the local water utility..." Thus, a rainwater reclamation system is utilized to collect and store water from the entire roof in a 10,000 gallon roof-mounted tank. Based on Boston's average annual rainfall of 44 inches, Appendix SM.1 shows the potential of such a reclamation system. The use of this stored water is two-fold: the potential energy is used to generate electricity and the water is used to fill the water feature in the Plaza.

To generate electricity, the water is dropped at specific intervals down a vertical pipe where it spins a turbine at street level. Here, the water is stored in another tank to be used in the water feature. The electrical generation component of this recollection system is a direct result of the coordination between the electrical and lighting teams and is used to power water feature lighting as well as a Public Sustainability Knowledge (PSK) Initiative system in the Plaza. This PSK Initiative system uses LED fixtures to create a green glow within the plaza when electrical generation occurs in the water reclamation system, serving as a beacon of sustainable practice to the public. To increase visibility, the micro-hydro turbine is housed in a transparent housing at street level. The detailed electrical and lighting descriptions of this system are provided in the *Electrical Systems Narrative*. While the electrical generation of this system is trivial in regards to a building of this scale (135 kWh/$20 annually), the impact of such a lucid display of sustainable design goes without measure.

(AES) Phase Change Materials

(VE) Creation of a building that reacts quickly and efficiently in order to satisfy the needs of its occupants has traditionally come at the expense of thermal stability. Phase change materials (PCMs) are used to provide three major benefits to the building: decrease building peak load, decrease building energy consumption, and increase thermal stability. PCMs allow for latent thermal storage to be placed within all personal office rooms in the form of specially constructed

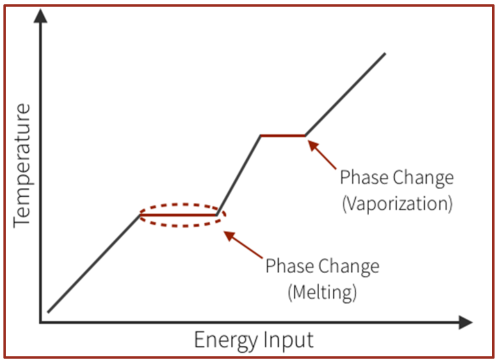


Figure M.5: PCM Temperatures

lay-in ceiling tiles. PCMs in panel form create the canted ceiling panels as coordinated with and described by the lighting design team in the *Electrical Systems Narrative*. This is especially useful in the case of 888 Boylston Street, where thermal loads fluctuate greatly, as seen in the case of a conference room or exterior office. Rather than waiting for the HVAC system to react to the rapid change in room load, PCMs instantly begin to absorb heat and maintain a consistent space temperature.

The mechanical team has selected the PureTemp 20 PCM with properties outlined below.

Melting temperature: 68°F | Heat of fusion: 171 J/g | Density: 0.95 g/mL

$$Q_{latent} = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)]$$

$$Q_{sensible} = mC_p(T_f - T_i)$$

Equations M.2: Latent vs. Sensible Thermal

The material within the PCM panel is selected to melt near room set point, storing heat latently through the process of melting (see Figure M.5). This gives the PCM a distinct advantage over sensible heat storage alternatives through its utilization of a material's heat of fusion (Δh_m) to determine total heat capacity as shown in a comparison between sensible and latent heat storage in Equations M.2. PCMs are applied in lay-in ceiling tile form in all private offices and conference rooms, with specific locations shown in Appendix SM.3. In this configuration, the PCMs provide a maximum daily energy storage capacity of 2,400 kWh providing a total annual savings of $121,000, as supported in the calculations in Appendix SM.1. If a value engineering option is needed, the amount of PCM application can be scaled back, as described in the *Value Engineering* section. Traditional thermal storage systems (e.g. ice thermal storage) simply shift

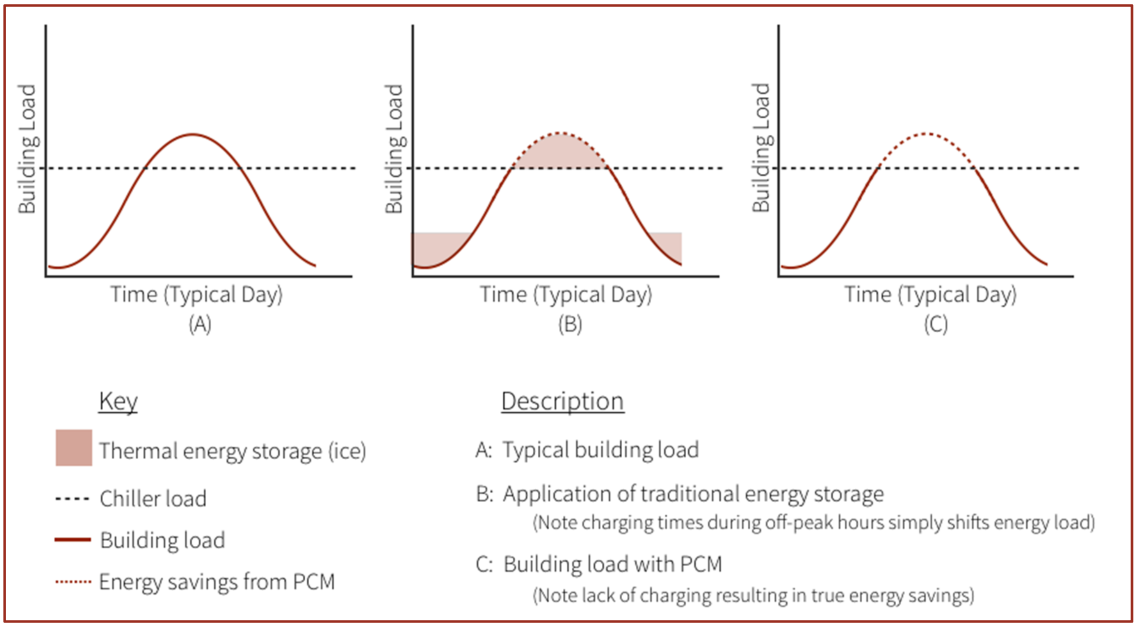


Figure M.6: PCM Building Energy Savings

the load from an on-peak hour to an off-peak hour. Since PCMs store energy latently, they avoid this energy intensive freezing - or "charging" - period and can simply "release" the heat back into the space once the load is removed. Night time purge is implemented to reset the temperature of the PCMs, and the fan energy requirements for this process are eliminated through the use of a Stack Effect Ventilation system (described in the following section).

(AES) Stack Effect Ventilation for PCM and Nighttime Setback

The stack effect – or the vertical movement of air due to a temperature gradient - occurs naturally in all spaces. As warm air is introduced to a cooler space, the warm air rises, causing an airflow equal to a value described in Equations M.3. The stack effect is more pronounced in high-rise structures where air can flow uninterrupted over long distances. As previously stated, the choice to specify a chilled beam system allowed for more open space within the building's mechanical shafts. The mechanical team found that one 3' x 4' Stack Effect Ventilation duct in each of the building's two mechanical shafts would meet PCM airflow requirements. These two ducts will be used to pull cool outside air over the PCM modules, allowing for them to reject heat to this airstream rather than to occupied space. The PCMs solidify and "reset" for the following day.

$$Q = 60C_D A\sqrt{2g\Delta H_{NPL}(T_i - T_o)/T_i} \qquad (T_i > T_o)$$

or

$$Q = 60C_D A\sqrt{2g\Delta H_{NPL}(T_o - T_i)/T_o} \qquad (T_i > T_o)$$

Equations M.3: Airflow via Stack Effect

ADDITIONAL SYSTEM DESIGN CONSIDERATIONS

Southern "Sawtooth" Façade

The decision to implement this Sawtooth Façade on the southern face of 888 Boylston Street was heavily driven by the needs of the electrical team. The continuous communication between design teams resulted in positive benefits shared across all engineering disciplines. This unique façade facilitated the integration of several key technologies. The recessed area created at the exterior perimeter of each floor of the façade gives a small ledge in which a photovoltaic system can be mounted, dramatically increasing the total area (and thus output) of the building's PV system. See the *Electrical Systems Narrative* for a detailed explanation of this integrated PV system. Additionally, the Sawtooth Façade causes the building to naturally function as its own shading device via the protruding slab, which has the biggest impact on the mechanical system design (see figure M.7). The implications of this natural shading creates an inherent benefit within the mechanical design by lowering overall solar gain within the building. Additionally, the curtain wall features a 50% transmissivity for the lower portion of view glass and a 90% transmissivity on the upper portion. A Trane TRACE 700 energy model of the Sawtooth Façade shows that the increased shading of the façade reduces building-wide cooling load by 47,600 kWh per year, a 1.5% reduction. In itself this reduction can

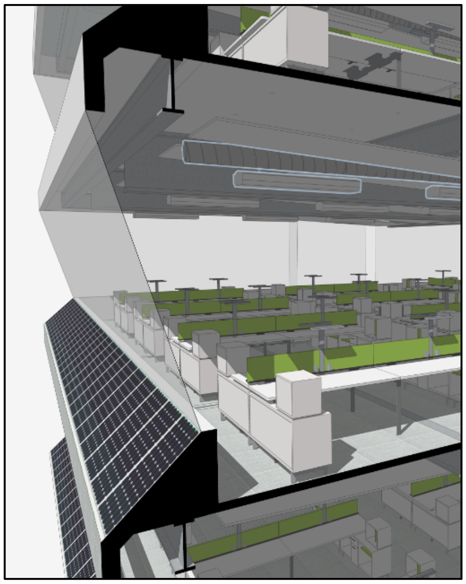


Figure M.7: Sawtooth Façade

be seen as insignificant, but as an innate feature of this new façade, one that already has numerous benefits, this reduction is yet another area in which mechanical energy savings are realized. These small savings embody the mechanical design team's philosophy where attention to detail results in large end-goal savings.

Low Velocity and Static Pressure Design

The goal of low velocity and low static pressure design within the airside mechanical components was to reduce the overall resistance - and thus fan power requirements - of the entire system. By lowering fan power requirements, the design team was able to select smaller fans to save on initial cost. The lower load on the fans results in reduced operating costs over the lifetime of the building. Additionally, lower powered fans required less sound attenuation systems to be specified through coordination with the acoustical designer.

Low Velocity Air Handling Units

Traditional air handling units are often sized with a coil velocity of 500 fpm to help reduce condensate spray off of the coil and maintain a small footprint, and a higher velocity allows for a smaller overall enclosure. However, this high velocity across the coil comes at the cost of significant pressure drop within the air handler.

The AHUs within 888 Boylston Street serve as the primary air handlers and utilize a low velocity design based on the coil velocity of 300 fpm. Due to the choice to specify chilled beams, a large portion of the building's cooling load is satisfied through chilled water, reducing the overall airflow needed within the building. Smaller air handlers are needed to meet this lower initial airflow allowing for them to be oversized in order to lower coil velocity and still requiring less space than a traditional all-air VAV system. While it can be argued that the oversized air handling units add undesirable cost to the design, the significant pressure drop changes outlined in Table M.5 prove that the trivial amount spent to increase the size of the air handler results in significant savings through the reduced fan requirements.

AIR HANDLING UNIT	VELOCITY	AHU STATIC PRESSURE
HIGH VELOCITY DESIGN	500 FPM	2.50 in.wg
LOW VELOCITY DESIGN	300 FPM	1.00 in.wg

Table M.5: Low Velocity Air Handling Unit Implications

Low Static Pressure Ductwork

The choice to move to a chilled beam system significantly reduced the overall airflow within the building and resulted in a dramatic reduction in duct size, leaving the mechanical team confident that the design of ductwork at 0.050 in. w.g. per 100 feet (half of the typical pressure drop) and the accompanying slight increase in duct size would still leave room for the stack ventilation system. The largest supply main duct saw an increase of 12" per side (68" x 68" to 80" x 80"), but this small compromise results in significant savings through lowered fan power draw with calculations showing a savings of $57,000 per year. Overall system pressure implications on overall system pressure are shown in Table M.6 and savings are shown in Table M.7.

DUCTWORK	DESIGN STATIC PRESSURE	SYSTEM STATIC PRESSURE
HIGH PRESSURE DESIGN	0.100 in.wg	0.640 in.wg
LOW PRESSURE DESIGN	0.050 in.wg	0.350 in.wg

Table M.6: Low Static Pressure Ductwork Implications (Supply Air)

SYSTEM	PRESSURE LOSS		ENERGY CONSUMPTION		COST SAVINGS (ELECTRICITY)	(%)
	HIGH RESISTANCE	LOW RESISTANCE	HIGH RESISTANCE	LOW RESISTANCE		
SUPPLY AIR	3.14 in.wg	1.35 in.wg	898,400 kWh/year	508,800 kWh/year	$53,900 per year	43%
EXHAUST AIR	1.08 in.wg	0.91 in.wg	325,400 kWh/year	297,000 kWh/year	$3,900 per year	8.7%
TOTAL	4.22 in.wg	2.26 in.wg	1,224,000 kWh/year	806,000 kWh/year	$57,800 per year	34%

Table M.7: Low Resistance Design Results ($0.1384/kWh)

RESILIENCY

Mission Critical

In preparation for the possibility of a client requiring mission critical data and communication equipment, the mechanical design team collaborated with the electrical design team to create an interdisciplinary design capable of fulfilling Tier IV level redundancy within a data center. As the strictest rating, Tier IV redundancy has an allotment for 0.8 hours of downtime per year (99.995% run-time) with 2N redundancy. By definition, the system is able to run in emergency mode for 96 hours, twice the minimum length of time required by the client. This system is capable of handling a 70 kW computational load, or a cooling load of 20 tons.

Two fully-isolated cooling units are placed adjacent to the mission critical room to increase security during maintenance. Two air-cooled chillers are specified to handle the cooling load from the data center and are placed in separate outdoor locations to ensure system operability in the event of localized exterior damage. The decision to use two smaller air-cooled chillers is reinforced through coordination with the electrical design team. Rather than size a generator to meet the large load of the primary chillers, they are able to size to the much smaller load of the 20-ton air-cooled chiller pair saving in initial cost. See Appendix DM.1 for a diagram of this system.

IMPACT ON ADJACENT STRUCTURES AND PUBLIC WAYS

The boring involved with geothermal and sea loop systems within a large metropolitan area such as Boston requires careful consideration. To prevent interference with adjacent structures, the geothermal loops are placed 20 feet clear of the submerged highway and all surrounding foundations. The geothermal loops located below 888 Boylston Street and the plaza to the north of the building were coordinated with the Structural Team's foundation as shown in Appendix SM.4. The sea loop requires 1,800 feet of condenser supply and return pipe between the primary mechanical room and Charles River. As 888 Boylston Street serves as an icon of sustainable design with a dramatic reduction in waste production, energy use, and water use, the City of Boston was contacted at the onset of the design phase and was able to supply a small easement to the Charles River in an effort to show their commitment to the sustainable design ideology. To further aid the implementation of the sea loop, modern directional boring techniques are used to span the length between 888 Boylston Street and the Charles River, allowing the system to be installed without any major disruption of the public ways of downtown Boston including street and sidewalk traffic.

ZONING

Zones were created to ensure optimum occupant comfort and system controllability to help engage employees and customers alike. Individual zones were created for the exterior portions of the building to a depth of 10 feet in order to increase controllability and to decouple the occupants within the building from the impact of the outdoor conditions. Interior areas were grouped into zones by space type to allow for the manipulation of thermal comfort set points. Less critical areas and less-used rooms (i.e. storage) have a set point of 3 °F higher than adjacent spaces to further reduce building load. Executive offices, exterior offices, and conference rooms were placed in individual zones to directly cater to the rapidly changing needs and personal preferences of these spaces. Appendix SM.5 shows the specific zoning diagrams proposed for use in 888 Boylston Street. One thermostat is needed per zone in order to maintain proper space set points. A control valve modulates the chilled water flow on a per-zone basis based on input from the thermostat. The control of cooling capacity via a control valve, as required in a chilled beam system, is much cheaper than control of airflow via large VAV boxes.

PLUMBING

The domestic water system was designed in compliance with the 2009 International Plumbing Code. According to code, a domestic booster pump is required for this building. The building has approximately 2,000 water fixture units, so this pump is sized for 190 gpm, 350 ft hd, 30 HP.

Pipes were sized based on the 2009 IPC. The flow rates for commercial plumbing fixtures provided within the code are: water closets require 1.6 gpf, urinals require 0.125 gpf, lavatories require 0.5 gpm, and service sinks require 2.2 gpm. The pipes were sized by the summation of flow rate in gpm for each branch or main. Low flow fixtures are used throughout the building. ASHRAE Standard 189.1 was used for fixture low flow rates. Flow rates and connection sizes are listed below.

Water Closet: 1.28 gpf, 3/8 inch   Urinal: 0.125 gpf, ½ inch   Lavatory: 0.5 gpm, ½ inch

Water Use

In compliance with ASHRAE Standard 189.1, water consumption measurement devices for the domestic water supply are utilized throughout the building. Meters communicate daily data to a meter data management system and record hourly consumption of water.

FIRE PROTECTION

Fire Protection Systems

Fire protection systems were designed in compliance with IBC 2009. Specifically Occupancy Type B for office spaces, Occupancy Type M for retail, and Occupancy Type S-2 for parking garages. Per NFPA 13, the mixed-use area of the building is classified as light hazard occupancy. Automatic sprinkler systems are provided for all office, retail, and underground parking garage spaces. A double interlock fire protection system will protect the mission critical data center room(s). A standpipe is located in the core stairwell. All smoke control system components were designed in compliance with IBC 2009. Exhaust fans and ductwork are specified to withstand the temperature rise expected in the event of a fire. Inlets and outlets are located in a manner that does not expose uninvolved areas of the building to the effects of a fire disaster. All automatic dampers comply with approved and recognized design standards. Direct drive ECM fans are specified for use over belt driven fans due to the lower energy draw as well as the simplified maintenance process involved. Due to the height of the building (290 feet), a 750 gpm, 175 psi, 125 HP fire pump is required with two water mains that feed into the fire pump. A zone alarm control valve and a flow switch are located on each floor to provide greater control over the system.

Smoke Exhaust Systems

Methods

The pressurization method of smoke control was applied within 888 Boylston Street. Low pressure zones are created within smoke control zones (EA on / SA off), while high pressure zones are created within evacuation zones (EA off / SA on) to force smoke out of, and prevent the infiltration of smoke into, paths of egress.

Atrium

Due to the large ceiling height (~50 feet) within atrium and lobby spaces, smoke can effectively be exhausted at the ceiling level based upon the principle of buoyancy.

Stairwell/Elevator Shafts

A multi-point injection method of pressurization is used to maintain a higher pressure within the stairwells and elevator shafts in the event of a fire to ensure pressurization even when a door is open within the shaft (an event that could compromise a single-point injection system). If a fire is detected, emergency fans supply all shafts with outdoor air, as shown in Appendix DM.1.

Alarm Systems

Stairwell/Elevator Shafts

All shafts have alarm systems that trigger in the event of either: sprinkler water flow, heat detection, smoke detection, or pull station activation.

Atrium

The atrium contains beam smoke detectors that consist of a light transmitter and light receiver. Per IMC 2009, pull station alarms do not trigger a fire response within an atrium.

LIFE CYCLE COST ANALYSIS

Initial baseline costs for the mechanical systems of the building were first calculated utilizing RSMeans. Upper quartile values were used to represent the high-end design of 888 Boylston Street. For the office space, RSMeans provided a value of $42.85 per square foot for mechanical systems. This produces a value of approximately $15,215,000 for the office area of the building. Utilizing the location multiplier for Boston of 111.6%, the total building cost for the office mechanical systems is $16,980,000. For the retail space, RSMeans provided a value of $17.55 per square foot for mechanical systems. This produces a value of $1,053,000 for the retail area of the building. Utilizing the location multiplier for Boston of 111.6%, the total building cost for the retail mechanical systems is $1,175,000. Accounting for all other areas of the building, the total baseline initial building cost for mechanical systems is estimated at $21,800,000.

Initial baseline costs were verified, and costs for the sea loop system were calculated, using estimates for individual pieces of equipment. From these estimates, the sea loop system produced a total initial building cost for mechanical systems of $28,900,000. Assumptions for materials and installation are as follows:

- Geothermal Loop: $3,750 per loop
- Sea Loop: $2,250 per 20 foot diameter loop
- Cooling Tower: $50,000 for 120 tons
- Heat Recovery Chillers: $1,500 per ton
- Condensing Boiler: $75 per MBH
- AHUs: $9 per CFM
- Active Chilled Beams: $1,000 ea. (175 ft^2 ea.)
- Radiant Floors: $5 per square foot
- HVAC Ductwork: $12.50 per square foot
- Hydronic Piping: $8 per square foot

A life cycle cost analysis was conducted over a period of 50 years. This analysis includes initial costs, maintenance costs, replacement costs, and utility costs, as well as a 3% inflation rate. Using present worth analysis and comparing the total cost per year with annual energy costs from Trane TRACE 700, the sea loop system was found to have a payback of 18 years when compared to the baseline system. Over 50 years, the sea loop system saves $5,650,000 (16%) compared to the baseline system. See Appendix SM.6 for life cycle cost calculations.

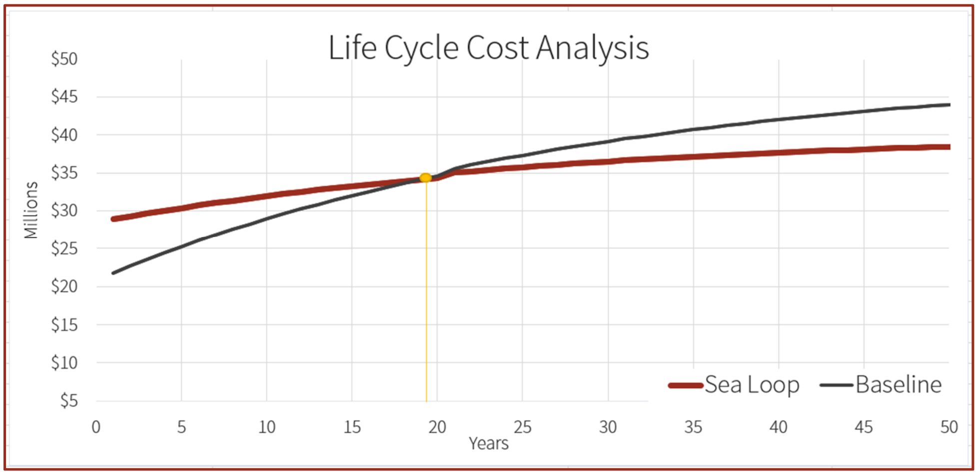


Figure M.8: Sea Loop and Baseline VAV Life Cycle Cost Analysis

LEED

Through interdisciplinary coordination, the design team achieved LEED Platinum (87 points out of a possible 110) on the 888 Boylston Street design. The mechanical team obtained LEED points through the utilization of the hybrid geothermal and sea loop system, the implementation of the rainwater collection system, and the reduction of energy use by over 50% of the baseline. For details of all LEED credits earned, see the *Building Integration Narrative*.

VALUE ENGINEERING

Hybrid Sea/Geothermal Loop

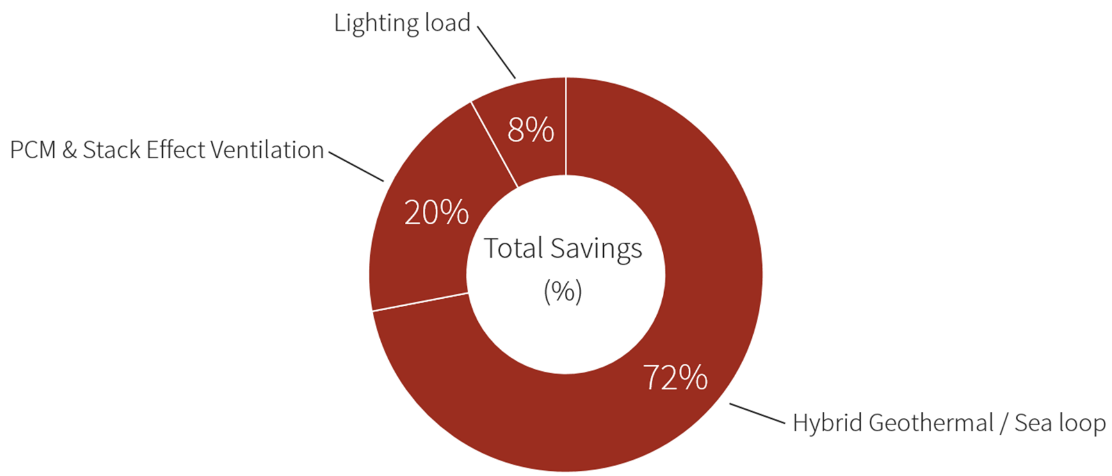
The hybrid sea and geothermal loop system is physically the largest component of the entire 888 Boylston Street project and while it has numerous desirable traits, it is an expensive and complex mechanical component. In the volatile world of building design there is the everlasting possibility of a project budget decrease forcing the entire design team to be ready and able to respond with a lower-cost design. As such, the mechanical team has prepared a value-engineering (VE) alternative for the hybrid loop in the form of a geothermal loop paired with a high capacity cooling tower system. By removing the sea loop the construction costs would fall considerably, as would any potential interference with the river and surrounding streets. This alternative system would see the already-specified 120-ton geothermal loop combine with a 650-ton cooling tower bank to meet the heat rejection loads of the four chillers. Clearly this system is very similar to the hybrid system which allows for a full VE design to be completed quickly and inexpensively in the case of a budget decrease.

Phase Change Materials

The modular nature of Phase Change Materials gives the system an impressive degree of flexibility enabling it to scale with any budget changes proposed by the owner. Ideally, all lay in offices within the building will harness this load-reducing technology, but if a budgetary issue were to occur, the scale of PCM application could be narrowed to only high-value rooms, or eliminated altogether. As was seen in the PCM VE section, the design changes for the PCM system can be performed extremely quickly.

CONCLUSION

The mechanical team utilized intelligent mechanical system design to reduce reliance on resources – both natural and man-made. This dedication to sustainable design resulted in the mechanical system showing a reduction in energy consumption of 79%. Through a combination of innovative mechanical system design, the implementation of the Sawtooth Façade, and through a substantial reduction on lighting load, the mechanical savings far exceed the 50% requirement. The total mechanical system payback (as compared to a standard baseline VAV system) is $601,000 annually. Of these savings, the PCM and Stack Effect Ventilation techniques contributed 20%, the hybrid geothermal and sea loop contributed 72%, and the lighting load reduction contributed 8%. Using the design principles established by the design team as a whole, the mechanical team was able to create an integrated, sustainable, and economic design – an iconic design – for the 888 Boylston Street project.



Annual Payback: $601,000

Integration | Structural | Mechanical | Electrical

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Electrical Systems Narrative

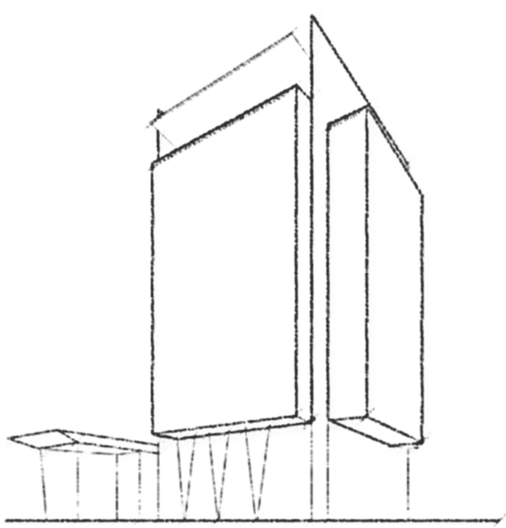
Electrical Systems Narrative

EXECUTIVE SUMMARY

Design Group 09-2016 is a multi-discipline consulting firm that specializes in structural, mechanical, and electrical designs. The design team utilizes the latest and most innovative technologies and techniques to provide their clients with efficient buildings that serve as icons of the sustainable design ideology.

Design Group 09-2016 has created the following design development document to outline the design goals and engineering systems for the multi-use 888 Boylston Street project in Boston, Massachusetts. 888 Boylston Street rises from a two-story below-ground parking structure to a three-story retail space capped by a 14-story office space. 888 Boylston Street is set to serve as an icon for the City of Boston through both its architecture and the design of its building engineering systems.

The design team employs comprehensive interdisciplinary collaboration to integrate engineering systems to a standard that is fitting for modern sustainable design. Design Group 09-2016 views a sustainable design as a facility that not only is efficient but also creates as minimal of a footprint on its surrounding environment as possible through the reduction of waste and consumption of resources. This organic relationship between systems creates a building capable of producing significant economic benefits for owners and allows for the full engagement of employees and clients alike.



888 Boylston Street Design Philosophy

Electrical Systems Narrative

TEAM 09-2016 | AEI STUDENT DESIGN COMPETITION

E

COLLABORATION

Collaboration is a fundamental component of integrated design. This idea drove the design team to begin interdisciplinary collaboration at project onset during the development of high-level design goals. Each discipline presented certain goals that would be otherwise unattainable without the direct and early coordination of building systems between the engineering disciplines and the architectural design. In the case of 888 Boylston Street, individual discipline teams participated in brainstorming sessions to generate sustainable ideas that are currently at the forefront of modern architectural design. These sessions led to an abundance of ideas that were closely aligned to the team's core design philosophy of creating a pioneering icon of modern sustainable design within the heart of Boston, Massachusetts. These goals required collaboration between structural, mechanical, and electrical design teams to be realized at their full potential. For example, the implementation of an exposed structural ceiling required specific types of both mechanical and structural systems. Further coordination was essential to ensure these two engineering systems integrated effectively into the daylighting strategies required by the lighting design team to further boost worker engagement and productivity.

PEER REVIEW

With the complex engineering systems required to fulfill the goal of designing 888 Boylston Street as a low-impact, sustainable facility, came a need for thorough review of all design decisions. The design team developed and implemented a multi-faceted review process in which all design documents were reviewed first by another member of the Design Group 09-2016 team, and secondly by a design engineer at a partner professional firm. To ensure a comprehensive interdisciplinary analysis, the in-house review of each discipline's document was performed by a member of a different discipline, while the industry review was performed by a professional engineer of the same discipline as the document being reviewed.

OVERVIEW OF SYSTEMS *(AES): Denotes Advanced Engineering System* *(VE): Value Engineering Option Present*

Power

Additional information can be found on the one line diagram, electrical riser, and calculations provided in Appendix DE.8, Drawing DE.9 and Appendix DE.10 respectively. The calculations within the appendix demonstrate worst case scenarios. All panels specified are listed as NEMA Type 1. Bus duct is used for most of the normal distribution system as it saves on labor and material costs and is a modular solution for installation as compared to conduit which allows for future work, and prevents voltage drop issues in multi-story buildings. Panel schedules are provided in Drawing DE.10. Figure E.1 shown above displays the standard panel naming convention. Electrical space layouts can be found in Drawings DE.1 through DE.7.

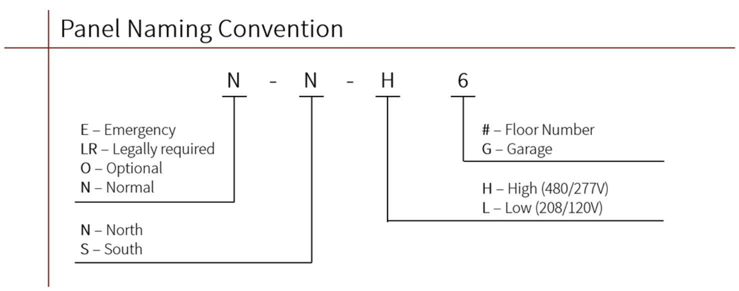


Figure E.1: Panel Naming Convention

Distribution

888 Boylston Street has an electrical system composed of a 480/277 V, three phase, four wire main distribution and 208/120 V three phase, four wire implemented for smaller electrical loads. The electrical design is fault tolerant and has 48-hour runtime in case of power loss as specified by the program. To accomplish this, two utilities are used to power the building as compliant with the critical system's Tier IV requirement. The two utilities were assumed to enter the building from the northwest on the lowest level parking garage. The utilities then enter the third floor transformer vault via a dedicated pathway for the utility. Each utility feeds into its own 5,000 kVA transformer which then feeds into its own 5,000A switchgear section in the adjoining main electrical room. These two switchgear sections are tied together for redundancy. From each switchgear section various branches are drawn for normal, emergency, legally required, and optional standby systems. Since the electrical rooms are located almost directly on top of one another, it was determined that the normal power should be fed throughout the building via a 3000 A bus duct and tapped off on each floor's electrical room to feed that floor's main distribution panels. All other distribution of feeders are fed via either EMT or PVC conduit for underground runs. All feeders are THHN conductors.

The grounding electrode system shall be connected to the ground via a concrete-encased ground electrode. The concrete-encased electrode consists of a #4 AWG bare copper wire connected to rebar (at least 20 feet) within the mat foundation system. The grounding electrode conductor is a 3/0 copper wire per NEC 250.66. The main bonding jumper of the switchgear is a 2/0 copper wire per NEC 250.102.

Resiliency

To provide clients with a safe, reliable electrical system, 888 Boylston Street's power distribution system was designed around the primary goal of resiliency. Power delivery is maintained during power outages to several key building systems including the emergency system, the legally required standby system, and the optional standby system. To provide resiliency, two separate utility entry points are used to supply power to the building. As such, these two utilities come into the building through two separate transformers leading to one switchgear which is split into two separate sections. These sections are tied together and in the event of the failure of one utility, the tie will open allowing the other utility to provide power for the whole building through the other switchgear section. Since a single utility transformer and both of the switchgear sections may be required to handle the building's entire load, both transformers and switchgear sections are sized to handle the entire building's electrical load.

In the event of losing both utilities, three generators located on the roof of the building will be powered through diesel fuel from several storage tanks. In total, there are three main fuel oil tanks located in the lower level of the garage and three separate day tanks on the roof. Each main tank has its own day tank on the roof and is connected through a pumping system. Day tanks were selected as they bring about an easy way for the utility to bring in new diesel, accomplish fuel redundancy, and provide less weight on the penthouse which aided the structural design team in the design of the penthouse system. For the two 200 kW optional standby generators, the tanks were sized to have enough fuel to last 48 hours each. For the generator to power the emergency and legally required systems, the tank was sized to provide a 24 hour fuel capacity. These fuel capacities led to a 5,000 gallon tank on the penthouse connected to a 5,000 gallon tank in the parking garage for the main generator and two 1,000 gallon tanks connected to their own 1,000 gallon tank in the parking garage for the optional standby generators. The floodplain for Boston, MA was analyzed and thereby determined to not be an issue for the fuel oil storage.

Close coordination with the mechanical design team was essential in ensuring safe and resilient operation of the exhaust ventilation systems of 888 Boylston Street in the event of a fire. Power to the building's mechanical fan systems must remain uninterrupted to maintain proper pressure throughout the building to keep paths of egress clear of smoke. Power is delivered to mechanical equipment for critical I.T. loads as discussed in detail within the *Mechanical Systems Narrative*.

(VE) Emergency Systems

The emergency systems within 888 Boylston Street include emergency and egress lighting, exit signs, fire alarm systems, fire pumps, elevator lighting, and mechanical ventilation. Emergency lighting, egress lighting and exit signs for the retail and office spaces are powered via an electrical panel located in the third floor emergency electrical room. A direct feed from the utility transformer feeds the fire pumps located on the third floor. Under normal conditions, the fire alarm systems is fed from a 120V circuit on each floor, and switches to battery power (located inside each fire alarm panel) in emergency scenarios. Elevator lighting and ventilation is powered by a panel on the garage floor. These loads are covered by a single 1 MW generator located on the rooftop of the building. Fuel cells were considered to provide the emergency energy generation through a value engineering process, however the cost of the system was determined to outweigh the advantages of the use of fuel cells. According to the National Renewable Energy Lab in 2014, the annualized cost of buying, maintaining, and purchasing fuel for eight hours of runtime per year for fuel cells was $5,300 as compared to $4,700 for a diesel generator. Although fuel cells have cleaner emissions than diesel generators, the amount of time the backup power would be on in a Tier IV system is so low that the budgetary issues outweigh the emissions issue. See the one line diagram as located in Drawing DE.8 for the electrical schematic and all electrical equipment sizes.

Legally Required Standby

Legally required standby systems include smoke evacuation, ventilation, and elevator loads. The smoke evacuation and ventilation for the office spaces are provided by AHUs located on the penthouse floor of the building, and by the exhaust fans located on the building's penthouse. The smoke evacuation for the retail floors and the parking garage is provided by exhaust fans on the third floor of the building. The elevators are supplied power by a panel on the first level of the parking garage. These loads are supplied by the same 1 MW rooftop generator that feeds the emergency systems of the building.

Optional Standby

With the possibility of a high end client such as bank may occupy one of the office floors, the electrical system for the client is required to be fault tolerant and concurrently maintainable for 48 hours. This led the design team to select a Tier IV system with a designed level of redundancy of 2N as Tier IV is the only system that meets these project requirements. This is based on the needs of the tenant and a sample plan utilizing the optional data center has been provided. There are two utility feeds into the building into two separate switchboards. Each switchboard feeds into an ATS that is also fed by its own generator. From the ATS, the system feeds into a busway that in turn feeds into a transformer or the mechanical panel. From the transformer, the power feeds into two UPSs that powers the IT load panel. Since the data center has cooling needs to remain operational, the mechanical design team provides two 20-ton chillers that feed two 20-ton CRAH units as compliant with the 2N redundancy.

Lighting

All lighting fixtures within 888 Boylston Street are specified as high efficiency LED luminaires. Through an analysis using COMcheck software (Appendix SE.2), the interior lighting electrical consumption is approximately 80% below code, exceeding the project requirement of being 50% under ASHRAE 90.1 2007. Such reductions have direct implications on reducing the building's cooling load, allowing the mechanical design team to reduce the overall size of their HVAC equipment, further lowering costs and increasing energy savings as described in the *Mechanical Systems Narrative.* Illumination calculations are located in Appendix SE.3, and the lighting fixture schedule can be found in Appendix SE.4. Renders of the lighting systems can be found in Appendix SE.5, with budgetary details listed Appendix SE.6.

Minimum lighting levels and recommendations were taken into account during the design of all areas within the building. The office floor was designed to meet a minimum of 40 Fc on the working plane and a minimum of 5 Fc on the floor. The avg/min ratio for the office floors was limited to approximately 3:1. All conference rooms and office rooms were designed to meet a minimum average of 20 Fc on the floor while limiting the avg/min ratio and max/min ratio. The emergency lighting was designed to provide a max/min ratio of at least 40:1 as specified by NFPA 101. The retail space was designed to meet an average of 5 Fc with an avg/min ratio of 4.0. Illumination printouts using AGI32 are located in Appendix SE.3.

(VE) Office

Individual workstations within the office area utilize Tambient® direct/indirect lighting fixtures. These fixtures provide both task lighting and general office ambient lighting while mounted directly to individual workstations. Circuited separately, the task light component of each fixture are switched on and off by an occupancy sensor mounted beneath the workstation. A dimming switch integrated to the fixture itself is also provided to allow users the ability to fine tune their task lighting from zero to sixty foot candles. The uplight component is controlled by both time-clock scheduling and photosensors, all integrated to a Tambient® CCH-EN-02 wireless dimming hub shown in Appendix SE.7. Twelve photosensors are placed on each office floor to control the uplight components of the Tambient® fixtures, offering occupants access to optimum levels of daylight throughout normal work hours. Office lighting is shown in Figure E.2, and layouts of the systems are shown in Drawing DE.6.

Figure E.2 - Office Lighting Rendering

General lighting around the core of the office levels consists of downlights utilizing cutting-edge Xicato® XIM LED modules. Downlights employing XIM modules are able to operate via 48V DC distribution routed from centralized power supply units (PSUs), each powering up to five luminaries. The downlights used in the office areas are the 9000 XIM Downlight supplied by Efficient Lighting Systems (ELS). Additionally, ADL 90 LED Pendant fixtures – also using XIM LED modules – are used throughout the office spaces, further leveraging the strengths of low voltage power distribution. These pendants illuminate collaborative workspaces allowing users to engage one another in a seamless manner. These downlights are also utilized in the conference rooms and private offices. Each conference room contains a vacancy sensor, dimming switch, and a scene controller to allow for a high level of control. Each private office contains a vacancy sensor and dimming switch. Each of the private offices and conference rooms along the perimeter of the building have a photo sensor to allow lights to be dimmed throughout the day. This system is shown in Renders SE.5. 5 & 6.

A potential downside to a lighting system that utilizes workstation-mounted luminaires is if a future tenant was to move into the space there may be a need for a different furniture layout than what is currently installed. However with minimal amounts of conduit in the exposed ceiling, a future tenant is provided with a clean slate for a new lighting fit-out.

<u>Office/Food Hall Entry</u>

The entry to the office tower provides a welcoming, invigorating atmosphere to employees while limiting direct glare into the lobby areas through abundant indirect cove lighting. Office workers are greeted with a large display showcasing the energy savings generated through the many sustainable designs within 888 Boylston Street, providing passersby a real-time visualization of the PSK Initiative (Render SE.5.7) as discussed in the *Building Integration Narrative*.

<u>Retail</u>

Consistent with the design goals of 888 Boylston Street, retail lighting employs LED track-based fixtures with LED modules capable of providing a high Color Rendering Index (CRI) to ensure full bodied colors are present throughout the space. A combination of spot lighting and flood lighting are employed to draw shoppers throughout the space. Lucent Lighting Prospex® Spot LED track with 20° and 60° optics are used, again utilizing Xicato® XIM LED modules with the *Artist Series* module to provide a CRI of 98. Grazing fixtures are used to emphasize certain aspects of the retail space. This lighting system is visualized in Render SE.5.4.

<u>Parking</u>

Efficacious LED parking garage luminaires are standard throughout the multi-level parking garage structure and are interconnected through a complete and encompassing lighting control network. Parking areas utilize Visionaire Lighting Bow LED at 119 lumens per Watt.

(VE) <u>Street Level Plaza</u>

The street level plaza utilizes pedestrian-scale LED bollards and decorative LED pole fixtures to draw people into the building. General lighting is provided by simple, yet visually striking inverted-L-shaped fixtures, creating an inviting yet calming aura across the plaza. Additionally, green-colored LED lighting further discussed in *Sustainable Design and Construction – Hydro Power*, serves as a visualization of the PSK Initiative. This is shown in Render SE.5. 1, 2, &3.

Daylighting

Studies have proven that when employees are exposed to daylight during working hours, they are more productive and healthier than their counterparts who lack open access to daylight. Daylight also aids in the energy usage of the building by reducing interior lighting loads and heating loads.

(AES) (VE) <u>Office Daylighting</u>

Throughout the design process, daylight control was key in influencing office architecture, mechanical systems, and lighting systems. The daylighting system was designed to block direct sun for the majority of the cooling season from May 1st through September 1st and to allow in direct sun during the heating season, eliciting a reduction in cooling and heating loads

At the onset of the design process the design team was tasked with creating a shading system for the south façade of 888 Boylston Street. A double-tiered external shading system with an internal light shelf was originally presented as a suitable solution to controlling daylight on the building's south façade. The original iteration's windows span 12.5 feet floor-to-structure allowing for an abundance of daylight with a flared-edge external light maintaining optimal shading performance on the working plane. An interior partition was placed along the window on the floor to block excess direct glare while reducing vertigo of office workers walking directly beside the window.

However, the design team felt that this iteration did not fully align with the project goals of 888 Boylston Street, and proposed a significant redesign of the building's south façade to create a comprehensive approach using ideas from the entire design team. The final proposed design includes a unique architectural feature creating a "sawtooth" appearance on the building's southern façade. This Sawtooth Façade design was conceived as a way to use the building itself as a shading device while providing a location on the exterior of the building for mounting solar panels at a more effective angle than traditional vertical building-integrated photovoltaic systems. Coordination between the structural and electrical design teams was key in integrating the structural modifications to best accommodate the south-facing PV system. The design consists of two solid exterior wall sections, one rising from the floor and the other spanning the top two feet of the curtain wall. The angled exterior glazing spans between these two partitions providing a ledge for the mounting of a PV system. There also is an interior light shelf allowing for improved daylight delivery as well as automatic blinds to prevent glare on the working plane. The curtain wall features a 50% transmissivity for the lower portion of view glass and a 90% transmissivity on the upper portion to allow for optimal daylight delivery. A section of the Sawtooth Façade is shown in right side of Figure E.3 immediately following this page. Refer to the *Building Integration Narrative* for additional daylighting information and reference Appendix SI.1 for a visualization of the office daylight autonomy. While the Sawtooth Façade is an ideal design solution for the needs of 888 Boylston Street, the preliminary "flat" iteration stands as a dependable Value Engineering option.

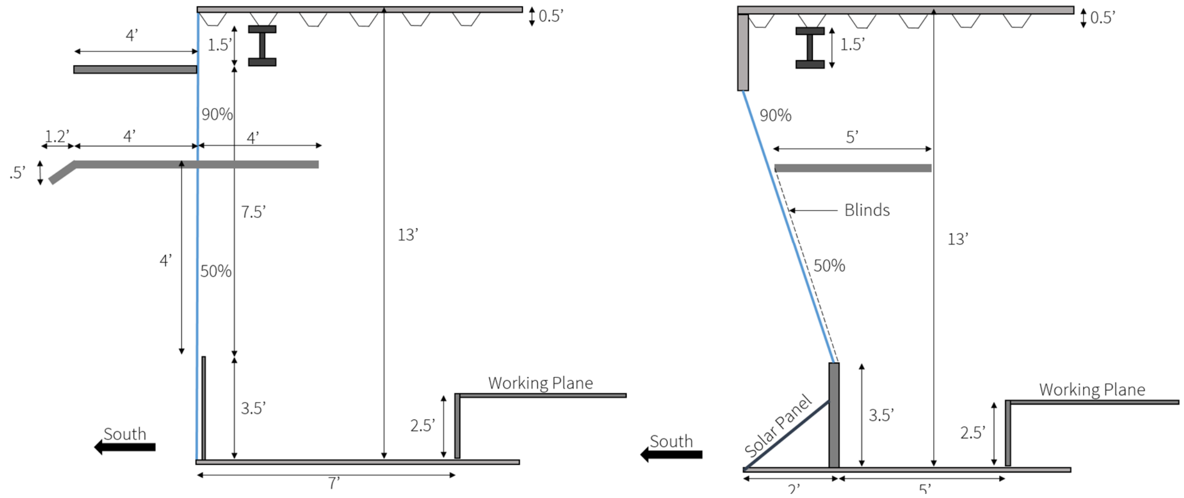


Figure E.3: Daylighting South Office Possible Elevations

<u>Sky Garden</u>

The design team analyzed which façade would be ideal for the sky garden on each office floor. Through use of DIVA for Rhino, the north façade was determined to be the ideal location for the sky garden as it provided the best combination of added daylight to the office floor as well as the most optimal view. The addition of the sky garden influenced the design of the prominent north façade and was a driving factor in the modified layout of the structural system at the building lobby storefront. More information can be found in the *Building Integration Narrative.*

Other Systems

Along with the power distribution, the low voltage and lightning systems layout were also provided. These systems include the fire alarm, security, lightning protection, and communication systems.

<u>Fire Alarm</u>

There are special requirements for the fire alarm design of 888 Boylston Street due to its classification as a high rise structure. The fire command center in the design is 220 square feet and easily accessible from the first floor, meeting the requirements specified by IBC 2009. The fire command center includes the emergency voice/alarm communication system control unit, a wired connection to the fire department, fire detection and alarm annunciator, status indicators and controls for the air distribution systems, a control panel for smoke controls to be used by firefighters, controls to unlock stairways simultaneously, sprinkler valve indicators and controls, emergency and standby system indicators, a telephone for firefighter use, fire pump indicators, generator controls, and a public notification system.

The fire department communication device is installed in each floor's exit stairway. The communication system operates between the fire command center, elevators, elevator stairways, electrical rooms, fire pump rooms, areas of refuge, and in the exit stairwells. Smoke detectors are found near mechanical equipment, transformers, electrical rooms, elevator lobbies, and the elevator machine room. Duct detectors are found in the main return and exhaust plenum where the cfm exceeds 2,000 and at the vertical duct connection that serves two or more floors. The main fire alarm control panel is on the first floor with fire alarm annunciators located in the fire alarm room on each floor. There is a Very Early Smoke Detection Apparatus to quickly detect a fire reducing damage to the data center equipment inside of the data centers.

Data

A backbone of fiber cabling is brought into the building with CAT 6A serving as the building's horizontal cabling. The cabling is brought to the office area via conduit and is stubbed up through a fire rated floor box to the floor above. Two data outlets are provided for each desk, in each private office, in every small meeting room, and for each of the eighteen wireless access points. Four data plugs are provided in the large conference room. From this cable design and a 25% spare allowance, a total of 495 cables were required, which lead to eleven 48-pair patch panels per office floor. Wireless access points are spaced 40 feet on center.

A Power over Ethernet (PoE) system is employed to power and connect phones and other telecommunication devices. For the Audio/Video (A/V) system, the conference rooms have a floor box with A/V connections from a laptop to the television.

Security

Several rooms such as the data rooms, electrical rooms, mechanical rooms, and storage rooms are secured via controlled key cards. Card readers are utilized in elevators during non-business hours and for high security floors, and are used at the turnstiles near the second floor security desk near the office elevators. A modern CCTV system is used to monitor security cameras.

Lightning Protection

UL Master Label System is utilized in 888 Boylston Street as recommended by NFPA 780. The lightning risk assessment showed a low chance of a lightning incident due to the geographic location as well as the surrounding buildings such as the Prudential Tower. However, for insurance reasons and best-practice design, a general lightning protection system was specified. Since this building is larger than 75 feet in height, all materials used on the exterior structure shall be Class II. General lightning protection on the roof was provided by air terminals. These air terminals are spaced at a maximum of 50 feet between each terminal within the middle portion of the roof. Air terminals along the outer edge of the building are spaced at a maximum of 25 feet between each terminal and within two feet of the outer edge of the building. These air terminals are a minimum of 1/2 inch diameter if copper or 5/8 inch diameter if aluminum. Rooftop mechanical systems require at least two main-size conductors located as far apart as possible with a minimum contact area of 3 square inches. At least two down conductors widely separated are provided for the tower of each wind turbine.

SUSTAINABLE DESIGN AND CONSTRUCTION

Alternative Power Sources

Various alternative power sources were considered for 888 Boylston Street including solar energy, wind energy, and hydro turbine energy. Selection and design of power sources were based on efficiency and the payback period of each technology. The design team is spearheading an effort to spur a renewed conversation on environmentally-friendly actions within the community as showcased by the Public Sustainability Knowledge (PSK) Initiative discussed in greater detail in the *Building Integration Narrative*.

(AES) Solar Energy

(VE) One of the primary sources of renewable energy lies in the form of a photovoltaic system. Potential locations for this system include three locations on the rooftop of the building as well as on a ledge of each office floor of the South facade of the building created from the Sawtooth Facade as discussed in the *Office Daylighting* section. All scenarios were run through a simulation to determine net capital cost, yearly net savings, and payback period with various types of solar panels using the System Advisor Model program that was developed by the National Renewable Energy Laboratory (NREL). This software takes into account annual weather data for a particular location along with federal and state incentives to determine the yearly power output from a selected PV module and inverter. Users of photovoltaic systems in Boston, MA are able to participate in the Solar Renewable Energy Credit (SREC) Program, providing monetary incentives per 1,000 kWh of on-site solar generation. Additionally, up to 30% of the original price of installed solar or wind systems can be deducted as a tax credit to the owner.

The selected PV design for 888 Boylston Street was based on the lowest payback period. However, if the client so desires they may choose an alternate photovoltaic system. The selected design utilizes the Kyocera KD315GX-LPB photovoltaic module which was chosen for the three rooftop locations due to its excellent solar-to-electricity efficiency. In total, 345 panels can fit within the desired space on the penthouse. A system configuration of 34 strings of 10 modules mounted at latitude was chosen, unified by tying into six SolarEdge inverters. The Solar World 340-350 XL Mono was chosen for the south facade. 30 photovoltaic modules are located on each floor's southern facade, with one SolarEdge inverter connecting to the panels on two separate floors. This leads to seven sets of 60 panels on the south facade. Losses due to shading by the Prudential Center were considered in the model. Figure E.4 shows the comparison between the panels at the three locations. See Appendix SE.8 for the specifications of the three solar panels.

PANEL OPTIONS	QUANTITY	CAPITAL COST	NET SAVINGS	PAYBACK	ANNUAL ENERGY
MECHANICAL PENTHOUSE					
1) KYOCERA KD315GX-LPB	120	$ 94,806.00	$ 9,421.00	4.4 Years	39,236 kWh
2) SW 340-350 XL MONO	112	$ 96,330.00	$ 6,500.00	6.5 Years	27,344 kWh
3) KYOCERA KD330GX-LPB	84	$ 70,646.00	$ 6,448.00	4.7 Years	26,878 kWh
MECHANICAL PENTHOUSE ROOF					
1) KYOCERA KD315GX-LPB	120	$ 94,806.00	$ 9,421.00	4.4 Years	39,393 kWh
2) SW 340-350 XL MONO	104	$ 89,449.00	$ 6,021.00	6.5 Years	25,373 kWh
3) KYOCERA KD330GX-LPB	90	$ 75,693.00	$ 7,201.00	4.5 Years	30,116 kWh
PENTHOUSE SOUTH FAÇADE					
1) KYOCERA KD315GX-LPB	105	$ 82,955.25	$ 8,243.38	4.4 Years	34,332 kWh
2) SW 340-350 XL MONO	98	$ 84,288.75	$ 5,687.50	6.5 Years	23,926 kWh
3) KYOCERA KD330GX-LPB	72	$ 60,553.71	$ 5,526.86	4.6 Years	23,038 kWh
OFFICE SOUTH FAÇADE - SAWTOOTH					
1) KYOCERA KD315GX-LPB	420	$ 331,821.00	$ 33,040.00	4.4 Years	137,872 kWh
2) SW 340-350 XL MONO	420	$ 361,235.00	$ 36,344.00	4.3 Years	151,578 kWh
3) KYOCERA KD330GX-LPB	462	$ 388,556.00	$ 38,514.00	4.4 Years	160,776 kWh

Figure E.4: Value Engineering - Photovoltaic System (Dotted line signifies best payback period)

(AES) Wind Energy

(VE) System Advisor Model was utilized to conduct an analysis to determine the feasibility of installing wind turbines on the penthouse level. Two models of wind turbines were considered for 888 Boylston Street; a traditional horizontal-axis and a vertical-axis wind turbine. The horizontal wind turbine used in the set of simulations was the XZERES 442SR. The preliminary design called for ten of these turbines divided between two banks, each located 65 meters apart on opposite sides of the roof. With an eight-meter spacing between the turbines, the preliminary horizontal-turbine design produced 251,431kWh of power yielding a total energy savings of $37,373 per year. However, the initial cost of this system is quite high, leading to payback period of 19.6 years.

When horizontal-axis turbines are placed closely to one another the air passing through them will become turbulent leading to a significant loss of energy production. Fortunately, vertical-axis turbines can be utilized to mitigate this issue. Vertical turbines may be placed more closely together than their horizontal counterparts without interfering with the energy production of da turbines. Improving on the original turbine design, the electrical design team specified Aeolos-V 10 kW turbines to be installed in the same locations as the aforementioned horizontal-axis turbines. Not only do they create a smaller wake while rotating, vertical turbines are generally easier to maintain, safer for wildlife, and more aesthetically pleasing. For these reasons, the team decided on 14 vertical turbines for the final design. Although System Advisor Model is unable to model vertical turbines with optimal accuracy, the two proposed turbines have similar outputs and wind-to-energy ratios, so the energy production is similar to that of the horizontal turbine. See Figure E.5 for images of the two wind turbines, and Figure E.6 for a graph of the expected monthly wind energy production. The specification sheet for the wind turbines can be found in Appendix SE.9.

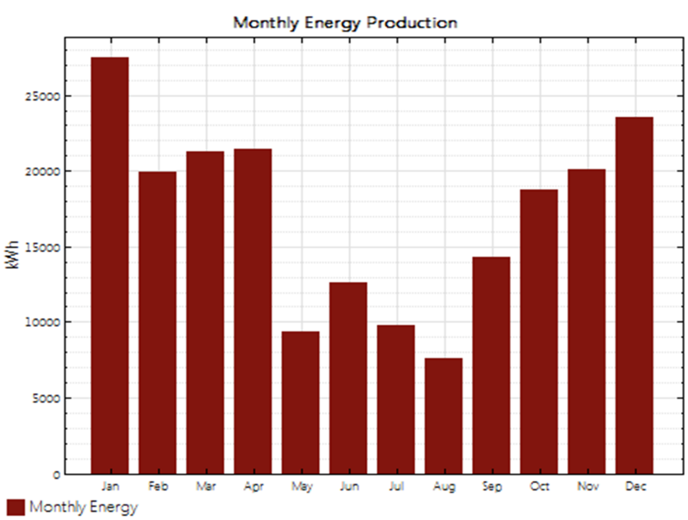


Figure E.6: Approximated Monthly Energy Production for the Vertical-Axis Wind Turbines

Figure E.5: XZERES 442SR (Top) Aeolos-V 10 kW (Bottom) (Source: SolarBK, Aeolos)

(AES) Hydro Power

Another renewable source of energy that 888 Boylston Street utilizes a rainwater collection system located within the penthouse of the building to collect and store rainwater during storms. The rainwater is first collected and stored on the rooftop, before passing down a pipe within the building to a water storage tank located beneath the storefront plaza. The water is then used by the fountain, putting yet another sustainable resource on display as a focal gathering point for visitors to 888 Boylston Street. A micro-hydro turbine is located at the bottom of the pipe on display in the main lobby of 888 Boylston Street. This turbine creates roughly 5,600 kW of usable energy on an annual basis. This energy is used to power green-colored LED luminaires within the plaza, informing pedestrians when the area is being powered by sustainable energy. This powering of the LED lights supplements the PSK Initiative by informing the community about the many ways that sustainable design can be incorporated into their everyday lives. The Canyon Hydro 751 micro-hydro turbine was selected in this design. By showing the public the benefits and savings associated with all three renewable generation systems, a broader knowledge of sustainability can be achieved through the PSK Initiative.

The project goal of sustainability can be fully realized as the building relies more on its production of renewable energy rather than power from the electric utility. In the main lobby of the retail and office entrance, the public is able to monitor the production of the PV systems and wind turbines through a display tied directly to the building's electrical meters. This system shows the real-time energy output of each sustainable generation technology along with their annual power outputs, monetary savings, and the ensuing reduction in carbon emissions. These choices were made as a direct result of the PSK Initiative.

Sea Loop

The hybrid heat rejection loop (more simply referred to as the "sea loop") is one of the major engineered systems implemented in 888 Boylston Street. While specifics regarding the design of the loop itself are detailed within the *Mechanical Systems Narrative*, the system requires a piping system to be horizontally drilled 1,800 feet from the project site to the Charles River Basin. To conserve space in the bored underground channel and to lessen the system's impact on adjoining structures and public ways, power is drawn at the building pumps through the building electrical distribution system rather than being routed beneath the roadway from the building, easing issues through quickened sea loop construction.

Office

Power for each workstation unit is provided by master-controlled advanced power strips that have multiple inputs for various loads used in a typical office. These advanced power strips automatically shut off the power supply to auxiliary desktop equipment such as phone chargers, printers, and fans when a "Master" device (e.g. user laptop) is removed from the workstation or powered down. In practice, such systems remove standby or idle loads once an occupant leaves their workstation. In this case, the design team recommends the tenants use ENERGY STAR rated laptop computers as the controlling devices. Additionally, "always on" outlets are also available to the users that remain unaffected by the removal of the "Master" device. The suggested advanced power strip is the Rocketfish™ 7 Outlet Power Manager due to its high level of reliability. The use of such control devices has been proven to reduce energy usage by up to 28%, with minimal increase in upfront cost and a quick payback period. When used in conjunction with ENERGY STAR laptop computers, total energy savings of 80% or greater can be realized. The additional cost of a master-controlled power strip is often minimal, with the proposed model requiring an investment of $3 per-unit at $17 per device over a traditional power strip that costs $5 to $14 per device. The typical payback period of advanced power strips is less than four years regardless of the model.

To maintain uniform ambient light levels in the office, the workstation-mounted Tambient® lighting fixtures cannot be plugged into the controlled outlets on the advanced power strips. This would lead to the direct and indirect portions of the fixtures activating throughout the day in conjunction with occupants leaving their workstations, creating unbalanced lighting patterns across one's field of view. To overcome this obstacle, the team chose to integrate the power and lighting systems of the office space by connecting the Tambient® fixtures to an "always on" outlet on the advanced power strip. This provides consistent power to the lighting fixtures, which are then manipulated by additional control devices. Like the load control provided via the advanced power strips, the direct task-lighting component of the Tambient® fixtures is adapted through an under-desk occupancy sensor adjusted to determine whether or not an individual is present at their workstation. The indirect ambient uplight generated by the fixtures remains at consistent levels throughout the workday, manipulated in real time by a comprehensive network of wireless photosensors (as outlined in the *Overview of Systems – Lighting* section of this document) to reduce the energy consumption of the lighting system. The downlight component of the Tambient® fixture is equipped with an integral dimming switch to provide a versatile lighting solution unrivaled in its ability to cater to user needs. Furthermore, the on/off operation of the ambient lighting component of the Tambient® fixtures is controlled via time-clock operation programmed into the CCH-EN-02 Wireless Dimming Hub shown in Appendix SE.7. The integration of electrical and lighting systems with the advanced power strips is visualized in Figure E.7.

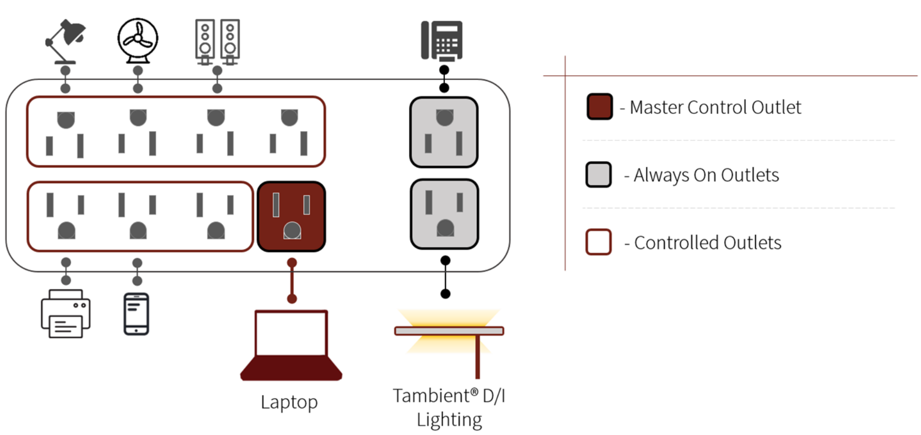


Figure E.7: Diagram showing integration of desktop devices to Advanced Power Strips (Source: Embertec Emberstrip® PC+)

Sustainability and economics are both key driving forces in the design process of 888 Boylston Street. The implementation of a significant number of low voltage LED fixtures utilizing the Xicato® XIM modules provides many benefits to the design of the power distribution system, including improved resiliency, increased maintenance efficiency, and simplified installation. This low voltage lighting solution uses power supply units (PSUs) installed remotely from the fixtures in the electrical room on each office floor to convert a higher AC voltage (277V), to a low voltage (48V) direct current power feed. In doing so, the vast majority of the lighting power distribution system is certifiable under UL 2108 - Standard for Low Voltage Lighting Systems allowing for the use of Class 2 circuiting. Such systems have a maximum power rating of 100 VA, allowing for 5 of the specified low voltage luminaires to be connected to a single PSU.

During the construction process, the ELS 9000 XIM LED downlights specified in the aisles and transitional spaces around the office core result in a reduction in both shipping costs and shipping materials when compared to their traditional 277 V LED counterparts. This is due to reduced luminaire sizes resulting from removing the integral power supplies from the fixtures. The ADL 66 and ADL 90 LED pendants supplied by ELS continue this trend, seeing reductions in overall fixture size for similar reasons. These design choices establish a forward-thinking approach to reducing construction waste while ensuring an environmentally-conscious approach to building sustainability.

SAVINGS CATEGORY	MATERIAL	LABOR
ACCELERATED FIXTURE INSTALLATIONS	--	$ 91,240.87
REDUCED CONDUIT & WIRING	$ 32,391.66	$ 123,548.25
	TOTAL SAVINGS:	$ 247,180.78

Figure E.8: Estimated Savings – Office L.V. Lighting

One of the most significant benefits of the classification of the lighting's low voltage wiring as a Class 2 distribution system is that it removes the need for licensed electricians during the installation of any Xicato® XIM-based fixtures. As the Tambient® fixtures and their control hubs are all powered via 120V convenience receptacles, the client experiences a significant reduction in labor costs related to the installation of nearly all lighting fixtures on each of the fourteen office floors due to neither the Tambient® workstation fixtures, recessed downlights, nor pendant fixtures requiring licensed electricians during installation. Rather, furniture installers can install the Tambient® fixtures, and apprentice electricians can install the Class 2 low voltage downlight and pendant lighting. Additionally, a significant reduction in conduit coupled with downsized wiring leads to a total estimated savings of $247,200 as shown in Figure E.8. Further information regarding the calculation process of these savings is provided in Appendix SE.10.

Furthermore, scheduling of construction related to the building's electrical systems was accelerated due to a significant reduction of conduit, and a lessened need for electrical contractors to access hard to reach plenum spaces throughout the building. The low voltage lighting system also provides benefits post-installation as all PSUs are remotely located in a centralized electrical room on each floor. This completely removes the need for maintenance workers to access the plenum space to repair or replace a defective PSU resulting in an increased level of worker safety.

<u>Office Lobby Escalators</u>

The motors of the two escalators represent a major load within the lower floors of the building. Traditional escalators run at full power regardless of time of day or occupancy which leads to high annual power consumption. By specifying escalators, energy can be saved by reducing or removing the motor load during periods of low use. A sensor located in front of the escalator entry point can determine when passengers are present and adjust the motor speed accordingly. The suggested office lobby escalators are Schindler's Eco Plus escalators. Another control strategy by the same manufacturer is utilized for the public entry. Sensor input enables the escalator to be able to vary its speed based on whether occupancy is detected. When no passengers are on the escalator, the escalators will stop. This control scheme was selected for use at office entrances as there will be periods when the escalators will be subject to consistent use such as during the morning and evening commutes when people arrive and leave work, and during lunchtime when people leave the office. Foot traffic besides these times identified is anticipated to be sparse. The use of this technology yields a 36% reduction in energy usage.

Elevators

Regenerative elevators are specified in order to save while generating electricity. Regeneration occurs when the elevator car is descending with a heavy load or ascending with a light load. The regenerative drive recovers energy and convert it into electricity for reuse. The selected regenerative drive can cut elevator energy usage by 50% when compared to traditional traction elevator systems. This regenerative drive also removes heat load created by drive or braking resistance. The elevators specified for 888 Boylston Street are KONE EcoDisc® elevators. Additional information on this system can be found in Appendix SE.11.

Retail/Food Hall

The power requirements of the retail and food hall areas include providing receptacles around the perimeter for cleaning, powering cash wraps, and powering lighting for displays. The retail space utilizes high efficiency LED spot lights for illuminating merchandise and cash wraps.

The escalator control strategy at the entry to the public space uses elevators manufactured by the same company as those in the office entry. There are two escalators leading to the retail area and two escalators leading to the food hall. The suggested public entry escalators are Schindler's Eco Premium. This technology slows down the movement of the escalator when no passengers are detected. This application was chosen because the number of people using the public escalators will be largely variable throughout the day. This technology can yield a reduction in energy usage by up to 32%.

Parking Garage

The parking garage has various receptacles provided for janitorial and other maintenance needs within interior spaces. Highly efficacious LED lighting is used to provide the necessary illumination of the space through the Bow LED luminaire supplied by Visionaire Lighting - yielding an efficacy of 119 LPW. These luminaires are connected using a complete and encompassing network of occupancy sensors. This system connects a single sensor to each fixture, with the controls maintaining the elevated lumen output in five minute intervals after occupancy of the space is detected. The fixtures dim to 10% of their nominal light output when the space is unoccupied. Using controls of this caliber can lead to an overall reduction of 76% in lighting energy demand by dimming fixtures when the areas are not in use.

Sustainable Design Summary

Compiling the savings discussed in the *Sustainable Design and Construction* section, Figure E.9 was calculated assuming $0.15/kWh.

TOTAL ENERGY SAVINGS / YEAR	ENERGY SAVED	MONETARY SAVINGS	PAYBACK PERIOD
ENERGY STAR LAPTOPS	736,243 kWh	$110,436.48	4.5 Years
MASTER-CONTROL POWER STRIPS	123,689 kWh	$18,553.33	~1 Year
PUBLIC ESCALATORS	34,636 kWh	$5,195.38	4.2 Years
OFFICE ESCALATORS	15,214 kWh	$2,282.14	4.8 Years
OFFICE ELEVATORS	365,980 kWh	$54,897.00	2.8 Years
SOLAR GENERATION	264,539 kWh	$39,680.85	4.4 Years
WIND GENERATION	249,153 kWh	$37,373.00	19.6 Years
TOTAL	1,398,041 kWh	$268,418.18	---

Figure E.9: Total Energy Savings per Year

COST CONSIDERATIONS

Using upper-quartile electrical cost data provided by RSMeans, an estimated value for a lighting system similar to that found within the 888 Boylston Street office area was calculated to be $2,436,300. Estimated costs of the proposed office area lighting equipment are $2,305,730, which is 4.4% below the target value before accounting for additional installation costs. This shows that the proposed lighting design is in the realm of a reasonable budget for a high-profile, innovative design. Additionally, savings realized through the decreased usage of conduit and the decreased labor costs (through the removed need for licensed electricians) within the offices saved $247,200, or 10.7% of the area's total lighting budget. Detailed calculations are provided in Appendix SE.10, and an itemized budget of the building's lighting systems is provided in Appendix SE.6.

LEED

The design team achieved a LEED Platinum rating (87 points out of a possible 110), with the electrical design team obtaining LEED points through significant use of on-site renewable energy sources in the form of rooftop-mounted wind turbines, photovoltaics mounted on the penthouse and south façade, and a micro-hydro turbine used to generate usable electricity from collected rainwater. Advanced power strips helped the design team realize a total energy savings of almost 80% for the office workstations. Energy efficient LED lighting was specified throughout the building leading to a reduction of over 80% over the regulations specified in ASHRAE 90.1 2007. For details of all LEED credits earned at 888 Boylston Street, see the *Building Integration Narrative*.

CONCLUSION

The combined electrical and lighting design team implemented a set of key design solutions to ensure that 888 Boylston Street is created as an icon of sustainable design, showcasing remarkable engineering features to the inhabitants of the Greater Boston area. Fully integrating structural, mechanical, and architectural elements into all electrical design decisions was vital in creating an organic representation of environmentally conscious design. The realization of an all LED lighting solution accompanied by a substantial use of low voltage and 120V plug-in fixtures allows for a significant building-wide decrease in labor and material costs. Innovative lighting control systems engage occupants of the building through an array of occupancy and daylight sensors, providing access to excellent levels of natural light while never sacrificing the usefulness of any space. Abundant rooftop wind and photovoltaic power generation, coupled with façade-mounted PV and rainwater collection systems help create a building which stands as an icon of intelligent and sustainable design for decades to come.