

Challenges and Lessons Learned from an Analysis of Three Zero Energy Buildings

Kate S. Hickcox, Pacific Northwest National Laboratory
Michael Myer, Pacific Northwest National Laboratory
Paul A. Torcellini, National Renewable Energy Laboratory
Rois Langner, National Renewable Energy Laboratory
Jordan Shackelford, Lawrence Berkeley National Laboratory
Alastair Robinson, Lawrence Berkeley National Laboratory
Cindy Regnier, Lawrence Berkeley National Laboratory

ABSTRACT

Zero energy buildings, or zero energy ready buildings, which are designed and operated by public or private commercial property owners can play an important role in reducing carbon emissions. This paper discusses lessons learned and key takeaways from an in-depth analysis of three zero energy buildings that took an integrated design and construction approach to significantly reduce energy use. Two of these projects are new construction and one is a retrofit to zero energy. Findings are based on project literature review, data analysis, and in-depth interviews with the building design teams and staff who were involved during the design, construction, and operation of the buildings. The paper addresses value proposition and cost data in such a way that other building owners can replicate the strategies and technology solutions in response to regulatory mandates or organizational goals. It also provides details on operational improvements taken at each zero energy building to enhance energy performance and increase the potential for load flexibility, and discusses challenges and lessons gleaned from design teams and building staff. The findings serve as a reference for building owners, designers, engineers, contractors, or others interested in, or involved with, the design, construction, or use of new or existing buildings. The paper also includes recommended pathways for widespread adoption of zero energy strategies that can be applied in various locations.

Introduction

Average global temperatures must be limited to well below 2°C above pre-industrial levels to avoid an irreversible and catastrophic climate change trajectory. Reducing average global temperatures will significantly reduce the risks and impacts of climate change (UN 2015). Zero energy buildings (ZEB)s are a critical part of the strategy to minimize carbon footprints and reduce global temperatures.

Public agencies and private commercial property owners have growing interest in ZEBs and zero energy ready buildings (ZEB-ready) in response to regulatory mandates or corporate goals. A ZEB is an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy.¹ Typically, the

¹ Department of Energy [Common Definition for Zero Energy Buildings, Campuses, and Communities](https://www.energy.gov/eere/buildings/articles/doe-releases-common-definition-zero-energy-buildings-campuses-and#:~:text=Generally%20speaking%2C%20a%20zero%20energy,energy%20in%20the%20building%20sector):
<https://www.energy.gov/eere/buildings/articles/doe-releases-common-definition-zero-energy-buildings-campuses-and#:~:text=Generally%20speaking%2C%20a%20zero%20energy,energy%20in%20the%20building%20sector>

priority is to have a substantial reduction in energy consumption compared to an energy code-compliant building—often 40 percent or more. The lower the designed energy use, the lower total amount of on-site renewable energy is needed, and the lower the carbon emissions of the building. Some ZEBs go beyond zero energy (ZE) and generate more renewable energy than the total energy used annually—the renewable surplus helps to lower the grid’s carbon intensity. ZEBs can achieve extremely low energy-use targets with an integrated approach toward energy efficiency and renewable energy (ASHRAE et al. 2019). When operating in an optimized manner, ZEBs can reduce energy consumption, peak power demand, and have the potential to increase resilience. Operation and design are equally critical to achieving ZE performance status. As with any building, maintaining the building to its design standards requires proper maintenance, monitoring, and education.

Finding the Projects for Use in the Field Validation Effort

Case studies are an effective tool for owners and designers when considering an investment in ZEBs, as they are brief and give a concise building overview, list energy strategies, and provide some overall performance data. Although case studies are a good start, in-depth information about a building yields valuable insights into decision-making processes, actual energy load compositions, as well as successes and lessons learned from technology implementation.

In January 2020, the National Renewable Energy Laboratory (NREL) issued a request for participation to identify candidate ZEBs for in-depth Department of Energy case studies. The request for participation was broadly circulated and sought to identify buildings meeting the following criteria:

- Energy savings of 40 percent when compared with ANSI/ASHRAE/IES Standard 90.1-2016. Typically, this would represent energy use intensity (EUI) values under 30 kBtu/ft²·yr.²
- Twelve months of measured energy performance data (preferably sub-metered data) and the ability to release data publicly.
- Access to design teams and building owners for interviews on strategies, technologies, and the reasons for making decisions around energy efficiency.

A team of experts from NREL, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory prioritized projects in April 2020. The team scored projects based on their innovation and performance, data availability, cost effectiveness, deployment potential, and probability that additional analysis could be conducted on existing building data. Three of the selected projects allowed for case study analysis³. This paper highlights findings from these three projects: the ASHRAE Headquarters (ASHRAE HQ) in Atlanta GA, the Frick Environmental Center (FEC) in Pittsburgh PA, and the Houston Advanced Research Center (HARC) in Houston, TX.

² The key to achieving a ZEB is a very low EUI. Many ZEBs have an annual EUI between 10 and 30 kBtu/ft²·yr. While some building sectors may require a higher EUI, a common thread is energy savings exceeding 40 percent from ANSI/ASHRAE/IES Standard 90.1-2016.

³ [Some of the featured case studies](https://www.energy.gov/eere/buildings/zero-energy-buildings): <https://www.energy.gov/eere/buildings/zero-energy-buildings>

Background on the Three Zero Energy Buildings

Although the three ZEBs in this project are in different states, all are in humid climate zones. In humid zones, there is a significant amount of energy consumed in the cooling and conditioning of buildings. It can be difficult to design a ZEB that can fulfill comfort requirements in humid zones; however, these three buildings met the goals by implementing innovative approaches. A breakdown of the three buildings compared in this paper is provided in Table 1.

Table 1. “At a glance” building comparison for the three ZEBs

	ASHRAE HQ	FEC	HARC
Case Study Team	NREL	Lawrence Berkeley National Laboratory	Pacific Northwest National Laboratory
Type of Construction	Retrofit	New	New
Location	Atlanta, GA	Pittsburg, PA	Houston, TX
Climate Zone	3A (warm humid)	5A (cool humid)	2A (hot humid)
EUI	22 kBtu/ft ² ·yr (est.)	25 kBtu/ft ² ·yr	15 kBtu/ft ² ·yr
Conditioned Area	66,700 ft ²	16,440 ft ²	18,600 ft ²
Completion Date	2020	2016	2017
Building Construction Cost ⁴	\$21.4 million (\$321/ft ²)	\$13.8 million (\$839/ft ²)	\$7.5 million (\$403/ft ²)
Primary CBECS Building Use ⁵	Office	Office, Education	Office
Description of Building Use	Offices, Conference/training rooms	Classrooms, education, community center, visitor center	Offices, Research Center

ASHRAE Headquarters

When ASHRAE was looking for a new headquarters building, they explored several approaches including building new, leasing existing office space, and renovating a building constructed in 1978. They determined that renovating the 1978 building (Figure 1) was the most cost-effective option by a considerable amount, and this approach also set an example for achieving ZE affordably in a retrofit project on a tight schedule. The total cost for the renovation project was \$21.4 million, which included the purchase price of the building, the cost of the photovoltaic (PV) system, renovation costs, and the value of donated equipment. This equates to a total of \$321/ft² for a 66,700 ft² building, which was \$200/ft² less than building new or leasing office space in the Atlanta area.

Through the in-depth evaluation of the building, the team found issues that compromised the indoor comfort levels and allowed moisture penetration because of a leaky envelope and many thermal bridges. Mechanical systems were at the end of life. To address these concerns, the project team incorporated several energy efficiency strategies. Of these strategies, the most

⁴ Costs not normalized by region or year

⁵ [CBECS Building Type Definitions](https://www.eia.gov/consumption/commercial/building-type-definitions.php): <https://www.eia.gov/consumption/commercial/building-type-definitions.php>

notable include; using hydronic heating and cooling coupled with air-source heat pump technologies and dedicated outside air systems (DOAS) to condition the space and decouple ventilation loads from heating and cooling loads; energy-efficient improvements to the building envelope and glazing; improvements to daylighting and electric lighting efficiency; and procurement of energy efficient plug load devices, as well as implementation of plug load energy management strategies. ASHRAE's commitment to achieving ZE was fundamental to their organizational mission and critical to the project's success. The design team's skill and continuous focus on the ZE goal was also critical in meeting the project goals.



Figure 1. The renovated ASHRAE HQ building with PV system installation was completed in October 2021. *Source:* ASHRAE

Frick Environmental Center

Completed in 2016, FEC was a joint venture between the City of Pittsburgh and the Pittsburgh Parks Conservancy—a nonprofit organization with a 25-year tradition of partnering with the city to restore its park system to excellence. Today, the FEC, an environmental education hub for the community and gateway to Frick Park hosts 10 to 15 employees in its offices daily and 75,000 visitors every year (Figure 2). The Pittsburgh Parks Conservancy approaches park projects with an emphasis on three principles: historic restoration, ecologic sensitivity, and user needs. The FEC building addresses each of these goals through an emphasis on building and designing in harmony with local ecology (for example restoring the previous fire-damaged center site and installing rainwater harvesting, distribution, and storage for watershed restoration) and serving as the park's home for educational programs that connect the community with the natural world.

The design team and the Pittsburgh Parks Conservancy desired to showcase how a state-of-the-art ZEB is attainable, even for a public project. The City of Pittsburgh and the Pittsburgh Parks Conservancy encouraged the FEC design team to pursue the highest-attainable sustainability and energy performance goals, including a Living Building Certification.⁶ When

⁶ [The Living Building Challenge](#) is a framework from the International Living Future Institute for holistic regenerative building design focusing on seven performance categories: place, water, energy, health, materials, equity, and beauty.

the FEC completed construction in 2016, it was the first public, municipally owned project in the country to hold a Living Building Certification.

The facility's core mission to provide environmental education to the public, led the City of Pittsburgh, the Pittsburgh Park Conservancy, and the design team to pursue the Living Building Certification. The building's efficient design, range of sustainability elements woven into its construction and operation, and on-site renewable energy generation translate to zero net energy and carbon over the lifetime of the facility. The project team used carbon credits from a local resource to account for carbon emissions associated with building construction activities and materials to achieve a net-zero carbon balance.



Figure 2. Frick Environmental Center image to be updated by Lawrence Berkeley National Laboratory.
Source: Pittsburgh Parks Conservancy and the Greenspace Alliance, Jeremy Marshall

Houston Advanced Research Center

The HARC was established in 1982, as a non-profit university consortium based on the vision and initiative of Houston-based businessman and philanthropist George P. Mitchell. HARC was formed to act as a technology incubator, bridging basic research and market applications. In 2001, the HARC mission was re-aligned to focus on sustainable development. The organization uses science and engineering to better understand and address concerns such as air quality, clean energy, water resources, and climate risk. When the HARC had the opportunity to build a new campus, they chose to design a living laboratory that showcases green building design, technology, and operations in action. They worked hard to make the building feel very “normal”.

In 2020, the International Living Future Institute certified the HARC Living Laboratory (Figure 3) as a net-zero energy building. Many aspects of the HARC ZEB design approaches highlight potential pathways for other building owners who may want to achieve the same excellent energy savings and carbon reduction results. The HARC team believes that ZEB success is “not rocket science,” it’s just knowing what to do and how.

Perceived cost can be a barrier to a successful ZEB project, as well as lack of understanding of various systems, such as geothermal. Some building solutions are affordable, scalable, and easy to apply in both retrofit and new construction. For example, the building

design engineer at HARC observed that relatively few contractors are familiar with, or are experienced in managing, advanced or networked lighting controls. Contractors' lack of experience increases the potential for failure. For this reason, the HARC design team opted to use traditional, less-complex lighting controls, including stand-alone occupancy, vacancy, and daylight sensors. Occupancy or vacancy sensors are a reliable and affordable way to make sure electric lighting is turned off when not needed.



Figure 3. HARC Living Laboratory in Houston, TX. *Source:* HARC

Setting Goals and Design Process

A successful ZEB project depends greatly on team members working together and engaging in ongoing, successful dialogue throughout the design and build process. One point that was repeated by building owners, as well as the architectural contractors, was the importance of designing with intentionality from the early stages. Setting goals and metrics early in the project, as well as setting up the team infrastructure to support communication and integration at an early stage, allows more time and money to be spent on the design phase of this project. Early costs pay off in the end with reduced time, effort, and money spent in later phases. The design team must identify what ZEB options are critical to the project and where owners are prepared to invest in technologies and techniques from the beginning. In an example of this early goal setting, all three case study buildings had an EUI target driving design decisions.

The cost of ZE approaches can be a barrier for some projects, however it has been shown that ZE success in projects is not necessarily tied directly to costs (NREL 2021). The three ZEBs in this report highlight how costs for ZE projects can vary significantly. Costs are impacted by a host of variables, including the materials and building systems that are chosen, project location and labor costs, project complexity, design decisions, and even the intended use of the buildings (e.g., office, education, public assembly, etc.). It should be noted that while some projects are more expensive, there are examples of ZEBs that have been developed at little- to no-additional costs compared to typical construction. Some ZEBs have come in at lower costs, like the ASHRAE HQ building (NREL 2021). Costs related to ZEBs can often be kept in very reasonable ranges when integrated design teams share the same ZE goals.

For the new HARC Living Laboratory, the design and construction team came together earlier than typical for a project, and key contractors were included in the early design phases, which helped integrate capital expenditures and operating expenses. Design meetings included the HARC financial team, and the owners were able to evaluate decisions through the entire process. The team evaluated a more expensive construction option with a lower, or more stable, operating cost. Although more money was spent in the initial design phase, construction costs were close to projected expectations because there were almost no change orders, due to the well-thought-out design. In contrast, many typical construction projects focus on the construction costs with only some consideration of the operational cost tradeoffs.

HARC felt their new building should embody the mission of the organization. Because of their work to optimize energy and water use, and continually monitor building system data, the HARC Living Laboratory exceeds (by 28 percent) its design and modeled performance targets. HARC designed and built a “smart” building which reports a large amount of data. HARC Living Laboratory is now a certified, net-zero energy building, meaning the building consumes less than what is produced on-site over the course of 12 months. Currently, there are less than 50 certified ZE office buildings in the United States, and HARC was the first in Texas.

ASHRAE developed a detailed owner's project requirements (OPR) document prioritizing specific programmatic and performance objectives for the project before starting work. This included objectives such as the conceptual design approach of the building, construction, and operation. Prospective design and construction professionals were evaluated using the OPR. As part of the OPR, ASHRAE developed detailed descriptions of the steps to achieve ZE status and ultimately integrated the owner's ZE requirements into construction documents. ASHRAE also engaged a commissioning agent to verify that the systems were performing as designed.

Leveraging “Achieving Zero Energy: Advanced Energy Design Guide for Small to Medium Office Buildings” the design team specified in the OPR a maximum site EUI of 21.4 kBtu/ft²·yr (ASHRAE et al. 2019). The design team used energy models to iteratively evaluate design options and systems in the design phase of the project. This enabled the team to optimize the building's energy consumption and meet the energy target. The final modeled EUI was 20 kBtu/ft²·yr which was slightly less than the EUI goal for the project (21.4 kBtu/ft²·yr). Challenges with metering the older electrical system has resulted in limited actual data.

Amidst all their goals (including wanting the facility to serve an educational function by demonstrating energy, demand, and environmental data through a web interface accessible to ASHRAE members and visitors), ASHRAE and the design team's commitment to achieve ZE led to the project's success. The project also successfully demonstrates an affordable transformation of an older building into a modern, ZE office.

The FEC design team's follow-through of original design intent resulted in a warm and inviting educational space which incorporates natural materials and an aesthetic connected to local crafts and resources. The facility's integration with the local environment and low energy usage raises awareness among visitors and occupants, which aligns with the city's educational goals to publicly showcase ZE principles. The FEC team sought and achieved their goal in creating a ZEB model for other public entities to reference.

Investment into features unrelated to energy efficiency include additional enhancements, such as rainwater management and landscaping, restoration of an historic stone gatehouse, and an outdoor amphitheater—all which the community can enjoy. As a public facility providing

long-term benefits to multiple user groups, the project is distinct from typical commercial investments which require more immediate returns on investment.

Featured Technologies and Techniques

While the design teams for the three ZEBs made many large and small decisions to accomplish ZE status, this paper highlights a select number of successful design and construction approaches that could easily be replicated in other ZEB projects.

Passive Design

Passive design is a set of design principles that leverage non-mechanical building attributes to attain building functionality within occupant comfort levels. Passive design relies on an understanding of the demands of different climates and how they impact siting, form, material choices, detailing, and construction assemblies. It allows designers to greatly reduce reliance on energy-consuming equipment and achieve highly comfortable and healthy buildings.

Both the FEC and HARC buildings were new construction projects and were designed with south-facing building orientations and a long east-west axis to take advantage of the optimal southern daylighting. For the FEC, the local topography allowed for the three-story building to be set into the hillside, providing a natural thermal mass that regulates the indoor air temperature throughout the year. The building is oriented with the north wall against the hill and partially below grade, while the south-facing wall faces downhill, with floor-to-ceiling windows that allow for daylight penetration deep into the occupied space—minimizing the need for interior electric lighting. Solar heat gain is controlled differently depending on the season. In the summer, a large overhang on the south side prevents direct solar gain during peak sunlight hours, while in winter, the low-angle sunlight enters the space and helps to heat the south-facing zones. A heating, ventilation, and air conditioning (HVAC) system that incorporates a natural ventilation mode also takes advantage of prevailing summer winds to meet ventilation needs when conditions are amenable, providing free cooling.

Building Envelope

Envelope is a critical component to ZE design projects. Envelope design can impact the type and size of mechanical equipment needed for a project. An efficient envelope design reduces a building's thermal gains and losses and allows for smaller equipment sizing and lower energy use for mechanical heating and cooling; this also reduces the burden of on-site renewables. A list of ZEB envelope features is provided in Table 2.

The ANSI/ASHRAE/IES Standard 90.1-2016 defines continuous insulation as insulation that is uncompressed and continuous across all structural members without thermal bridges other than fasteners and service openings (ANSI/ASHRAE/IES 2016). Continuous insulation is an essential element of a ZEB which improves the effective R-value (the measurement of a material's capacity to resist heat flow from one side to the other, or effectiveness of the insulation) of the structure. This approach produces a continuous air barrier that reduces air leakage and minimizes heating/cooling loads. The HARC building achieved continuous insulation with an envelope designed to provide excellent energy efficiency and moisture protection in Houston's hot and humid climate. Heat and moisture are common concerns in any building, and thermal bridging should be avoided in any location that requires mechanical

heating and cooling. Thermal bridging allows heat to bypass insulation layers, increasing heating and cooling loads. The HARC envelope minimized thermal bridges by extending the continuous exterior wall insulation to the underside of the roof deck, with no structural or floor slab penetrations. Spray foam insulation at the wall-roof transitions also helped to form a continuously insulated assembly. HARC achieved an R-32 roof by utilizing five-inch deep, continuous polyisocyanurate insulation on a metal roof deck. This treatment resulted in an R value that was 28 percent better than ANSI/ASHRAE/IES Standard 90.1-2016 requirements. The FEC design also emphasized a highly insulated envelope and achieved R-48 from its continuously insulated roof. The building is well insulated from cold winters and warm summers with six inches of rigid foam on 1 ½-inch metal decking (18 gauge) galvanized with an air vapor barrier. In addition, the roof's white finish achieves a high solar reflectance index, to further limit passive solar gain.

The three ZEBs used various exterior cladding approaches. The FEC used black locust cladding (vertical reverse board and batten) that has been used in the region as a rainscreen material for generations due to its local availability and natural resilience. The HARC building used a metal panel rain screen system with a top-vented, one-inch air gap next to the exterior insulation, that helps lower direct solar gains and reduces interior cooling loads. Renovating the leaky, 1978 ASHRAE HQ building envelope was critical in achieving ZE goals. The design team conducted a blower door test and thermal scans to reveal the original building's massive leakage rate and thermal bridges. The original building walls were insulated to R-3 values. To meet ANSI/ASHRAE/IES Standard 90.1-2016, the walls needed to be at least R-8. The design team exceeded these requirements and ran a sensitivity analysis to determine the point of diminishing return for the proposed improvements. The results from this analysis recommended R-17 for the wall assembly, R-35 for the roof (previously R-21), U-0.40⁷ for the window assembly, and a reduction from ~50 percent window-to-wall ratio (WWR) to 40 percent WWR. External shades for the south façade were also recommended at one foot depth, and air sealing was recommended to reduce the infiltration down to 0.011 cfm/ft². Air sealing is critical in any building project to reduce infiltration impacts on HVAC loads, and particularly in this building where moisture control is critical for enabling the radiant cooling system to properly function in such a humid climate.

⁷ U-factor is the reciprocal of R-value. High R values are better, lower U factor are better. U-factor represents thermal transmittance (rate of transfer of heat divided by difference in temperature).

Table 2. ZEB Envelope Features ⁸

	90.1-2016	ASHRAE HQ	90.1-2016	FEC	90.1-2016	HARC
Type of Construction	N/A	Retrofit	N/A	New	N/A	New
Climate Zone	3A (warm humid)		5A (cool humid)		2A (hot humid)	
Roof	R-25 c.i. ⁹	R-35	R-30	R-48	R-25	R-32
WWR	N/A	40 percent reduced from 50 percent by renovation	N/A	37 percent	N/A	21 percent
Exterior Walls	R-7.6 c.i.	R-17	R-13 + R-10 c.i.	R19 - R-22	R-13 + R-3.8 c.i.	R-50 ¹⁰

Low Energy Mechanical Systems

Ground-source heat pump (GSHP) technology was implemented at FEC and HARC as the primary means of mechanical heating and cooling. GSHP systems consist of an in-ground heat exchange with vertical or horizontal wells and heat pumps that use the ground as a heat sink or source to efficiently operate the refrigeration cycle. GSHPs take advantage of steady, mild underground temperatures that stay relatively constant year-round. GSHPs deliver heat at much higher efficiencies than those of a typical gas or electric resistance heater. The coefficient of performance (COP) (i.e., the ratio of heating or cooling output to the energy input to the system) for GSHPs generally ranges between 4.8 and 6.1. In contrast, air-source heat pumps typically have a COP of only about 3. Overall, GSHPs offer significant energy savings over alternative HVAC approaches; in the range of 30 percent to 60 percent or greater, depending on the system, climate, and application (Navigant Consulting, Inc. 2009). The high efficiency of GSHPs plays a large role in the FEC and HARC building's ZE status.

GSHP system design must consider the thermal conductivity of the well field and the way in which ground temperatures change in response to a building's heating and cooling loads. Modeling the heat flow to and from the well field is key to sizing the well field for reliable performance. The FEC and HARC design teams confirmed the systems' abilities to meet facility heating and cooling needs with a combination of building energy models and well field modeling. The FEC GSHP installation includes 18 vertical bores, 520 feet deep, to serve seven heat pumps that supply hot and chilled water to air handlers, hot water to in-floor radiant

⁸ Note that all three of these buildings were constructed at different times so they may have referenced earlier or later versions of the ANSI/ASHRAE/IES 90.1 Standard that what is shown in Table 2.

⁹ c.i. = continuous insulation, insulation that is uncompressed and continuous across all structural members without thermal bridges other than fasteners and services openings

¹⁰ R-50 was achieved through the combination of the wall construction (R-35 insulation) with a 1" air gap allowing heat from metal panels to transfer to air and vent upwards and reducing the amount of heat acting on the insulation.

¹¹ Includes the entire PV system cost including mounting structures, panels, and ground-mounted shading structures

systems, and chilled water to fan coil units. The HARC building uses a field of 36 vertical wells for 15 GSHPs that each support tailored space conditioning for a single room or small group of spaces. The design engineers used a test well and building energy model to accurately size the well field and gauge its functionality over time. The well field's performance is closely tracked and validated by temperature sensors and flow meters installed across the system.

FEC has a DOAS featuring a 3,500 cubic feet per minute unit with energy recovery enthalpy wheel and 12 variable air volume zones. Zone-level CO₂ sensors activate mechanical ventilation when needed, but natural ventilation was designed to be the primary means of space conditioning. Mechanical ventilation is used only when natural ventilation cannot meet the building's demand. Manual and mechanized windows on the building façade, and manually operated transom windows in the building interior halls, help draw fresh air from the south wall, through the building, and up through automated skylights in the north stair tower by using the "stack effect." Indicator light panels throughout the building illuminate green to alert occupants when conditions are appropriate for natural ventilation, based on air temperature and specific humidity. In this way, the facility encourages human interaction with efficient building systems, which works well at the FEC where the user base is very engaged. Approaches may need to vary in other commercial settings, where more automated control may be preferable (ILFI n.d.).

The original ASHRAE HQ building (before the retrofit) utilized a HVAC system that included a single chiller in the basement mechanical room, electric resistance heating, and a variable air volume air handling unit. Dehumidification used to be accomplished by maintaining a 55°F cold deck with electric resistance heat to control space temperatures through reheat. The replacement system separates the conditioning of fresh air including removing humidity from the sensible cooling of the space. This DOAS system uses the condenser heat to reheat the air after humidity is removed with the evaporative system. It also recovers energy from the outlet air stream and delivers it to the fresh air supply. A separate radiant-based system provides heating and cooling to the space for sensible heating and cooling loads.

Three 20-ton (70 kW) heat pump chillers were installed at ASHRAE HQ, which can generate hot and cold water with a COP of 3.2. Each unit can operate in heating or cooling mode to match the building's needs. These heat pump chillers feed radiant hydronic ceiling panels mounted throughout the building. The heat transfer efficiency and heat capacity of water, compared to the heat transfer of air, is very significant (by a factor of 4.23), making radiant panels a much more efficient option to move energy. The impact of the radiant system means that occupants can be comfortable in the building, even though the air temperature may be cooler in the winter and warmer in the summer. In addition, ceiling fans are used to expand comfort ranges in temperature and humidity. To mitigate any chance of condensation forming on (and dripping from) the radiant panels in the ASHRAE HQ building (especially in cooling mode), the design team decoupled the ventilation air and dehumidification from the sensible heating and cooling provided by the radiant panels. This was done by incorporating DOAS units that deliver fresh air in a dehumidified, cooled condition. Each DOAS unit is combined with a 72 percent efficient enthalpy wheel that recovers sensible and latent energy from the exhaust airstream and transfers it to the outdoor air entering the building. The units are also equipped with a packaged heat pump sized to provide final heating and cooling to the incoming supply air. The DOAS units supply 30 percent more outdoor air than the minimum required by ASHRAE Standard 62.1-2019.

On-Site Renewable Energy

ZEBs must generate as much energy as the building uses in a year. Many ZEBs use PV panels for on-site renewable energy. The amount of PV required to balance a building's load varies by climate zone, and even within a zone. Design guides and rules use the building size, building EUI, and climate to help estimate the PV panel size. Table 3 compares the PV features of the three ZEBs.

Table 3. Photovoltaic Features

	ASHRAE HQ	FEC	HARC
PV area as a portion of the gross floor area	27 percent	54 percent	26 percent
PV size (area)	18,112 ft ²	8,840 ft ² (estimate)	4,800 ft ²
PV location	Ground-mounted arrays plus roof-top array	Shade structure for onsite parking	Roof-top array
Rated power capacity	332 kW	162 kW	88 kW
Cost/kW ¹¹	\$1506/kW	\$3,654/kW	\$1,545/kW
Annual bldg. energy usage generated by PV panels	92 percent	136 percent	140 percent

At HARC, the building's south-facing orientation and sloped roof are well suited for rooftop PV power generation. HARC's iterative design process allowed for a modular or incremental approach to facility enhancements and upgrades. Based on budgetary constraints, the PV panels at HARC were installed in two phases.

In both 2019 and 2020, the expanded PV system at HARC generated around 95 percent of the renewable power generation predicted by the PVWatts® calculator tool¹². This tool was developed for the Department of Energy by NREL and enables prediction of PV generation output without the need for complex modeling or analysis.

For FEC to meet ZEB goals, the PV system (600 275-Watt panels with microinverters for higher system efficiency) was designed to produce more energy than the facility needs on an annual basis. While the cost of this system is higher than many PV systems, the cost included the parking lot shading structure. The total capacity of solar generation at FEC leads to a significant surplus in zero-carbon electricity. In 2019, the PV system produced 136 percent of the facility's annual energy usage, as illustrated in Figure 4. The grid-connected net-metered system provides this surplus back to the local utility grid. The PV system was purchased using in-house funding, so the site "owns" the renewable energy it generates.

¹¹ Includes the entire PV system cost including mounting structures, panels, and ground-mounted shading structures

¹² <https://pvwatts.nrel.gov/>

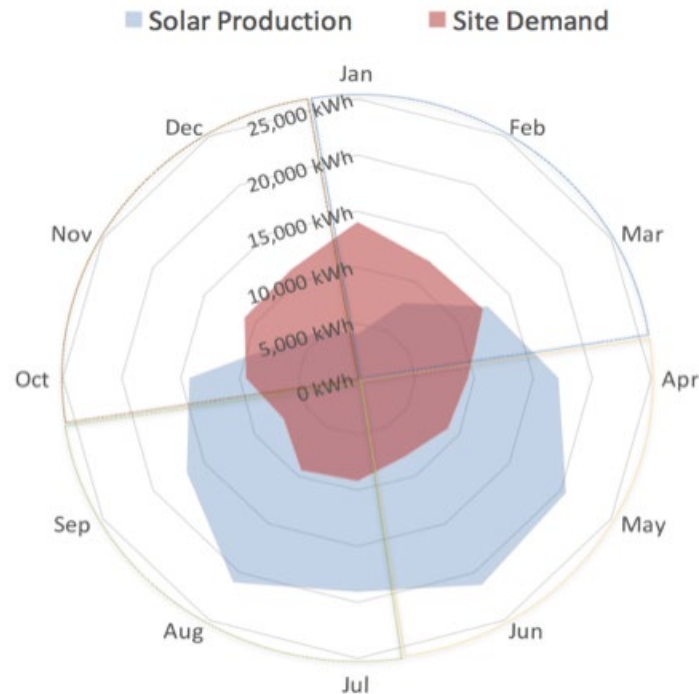


Figure 4. FEC 2019 solar energy generated (blue) exceeds site energy use (red) over the year. *Source:* Lawrence Berkeley National Laboratory

The ASHRAE HQ building installed a 332 kW PV system in October 2021. This includes two ground-mounted arrays and a 187-kW roof-top array. The system was installed 12 months after the building was operational. Based on eight months of PV data, the building is expected to cover 92 percent of its operational load with the solar panels.

Plug Loads and Monitoring

Energy use can vary slightly each year due to changes in building use, weather, and plug loads. Monitoring plug loads helps identify spikes or increased power usage. By monitoring the energy and occupancy data monthly, the energy manager can identify areas with low occupancy or usage and can customize the schedule. After the building had been operating for over a year in June 2019, HARC installed smart strips and a plug load monitoring platform on-site. Using third-party vendor services and products, HARC now monitors plug loads in each office. This information helps the building staff to target loads that may need to be better managed. Over time, HARC's plug load management efforts successfully identified standby loads operating after hours. Measures to address these loads successfully reduced overall plug load energy by 15 percent. In addition to the smart strips and third-party monitoring software, the HARC energy manager checks the building energy data each day and conducts a collective assessment of all technologies every six months. Monthly energy reports are distributed to staff and assessed internally to identify any areas for system improvements.

ASHRAE HQ implemented several plug load energy reduction strategies to keep plug load energy consumption low. This includes switching to using mostly laptop computers, deploying ENERGY STAR settings to shut down computers when not in use, reducing the

number of printers, and changing settings to power down when not in use. Most of the outlets are turned off automatically by timers when the building is not in use.

Operation, Occupant Education, and Behavioral Change

In addition to the technologies mentioned previously, HARC also reduces energy use through an internal campaign that encourages staff to conserve energy by turning off office equipment at the end of the day and notifying the energy manager of planned absences. The campaign started with a meeting to introduce HARC staff to the building design concept, what net-zero energy means, why energy reduction is important to HARC, and what changes staff would see in their day-to-day experience in the building. The team at HARC celebrates sustainability successes with the staff and provides recurring updates on the building milestones and the certifications they achieve. Success to HARC meant to become operational ZE by Jan 1, 2019—one year after finalizing the expansion of the rooftop solar plant. Thanks to their improvements in energy efficiency and to the buy-in from the full staff, they became net-zero by mid-November 2018. The HARC building is a very important resource to such a sustainability-focused research company. It was designed as a highly efficient building with the ZE goal in mind and is operated as a living laboratory to demonstrate what can be achieved with commercially available technologies.

At FEC, an important aspect of the building's design is occupant influence on, and adaptation to, the passive and active design elements; for example, manual controls for natural ventilation and efficient mechanical heating and cooling are coupled with a less formal dress code. During warm weather conditions, the temperature setpoint in the occupied spaces is allowed to drift up to about 75°F, and policies and office culture allow occupants to wear lighter and/or looser clothing. Similarly, during cold weather, occupants may choose to wear additional layers to stay comfortably warm to minimize mechanical heating needs. This is an example of how policy and behavior change, along with technology and design innovations, can be used to improve building performance.

Conclusion

To achieve truly sustainable and net-zero energy buildings, owners and design teams need to focus on integration and communication throughout the entire building life cycle—from the earliest design stages through to the use and maintenance of the building or site. This report shows the importance of engaging the full design team early and keep them involved by prioritizing communication throughout the project. It is equally as important to engage the end-users and staff of the building or site to ensure proper maintenance, monitoring, and education.

Perceived cost can be a barrier to achieving a successful ZEB project, as well as a lack of understanding of ZE technologies and techniques. The technologies and techniques described in this report can be affordable, scalable, and easy to apply in both retrofit and new construction. With the right planning and research up front, ZEB status can be achieved without paying a cost penalty or sacrificing occupant satisfaction and comfort. It is the hope that projects like these three ZEBs are shared, so design teams and local tradespeople become more familiar and comfortable with ZEBs and their systems, making ZEBs routine and affordable.

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