

# PHOENIX'S FIRST NET-ZERO ENERGY OFFICE RETROFIT: A GREEN AND LEAN CASE STUDY

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## INTRODUCTION

*Many in the construction industry view lean practices as a means for reducing cost and schedule while maintaining or improving quality. This paper argues that lean practices can also be used to promote energy savings throughout a building's life cycle. This paper presents a case study of an existing building retrofit in Phoenix, Arizona. The project owner, a general contractor, self-performed much of the building construction and worked to ensure the project team aligned around the project's net-zero energy goal. All building systems, excepting the walls and roof, were re-designed and re-constructed. After retrofit, the building has achieved net-zero energy consumption; that is, the building produces as much energy as it consumes on an annual basis. Deep building energy retrofits typically result in larger energy savings than operational changes alone can provide, as these retrofits take a whole-building approach to design (i.e., optimize the whole) and implement integrated project delivery methods (e.g., (AIA, 2007)). This paper discusses a net-zero energy retrofit and how lessons learned on this project could apply to other deep energy retrofits for commercial buildings (where "deep" refers to energy savings of 25% or more) that may significantly improve building value (Miller and Pogue, 2009).*

*The inefficiency of existing building stock supports the need for retrofitting: energy consumption in the existing building stock in the United States accounts for approximately 41% of the total primary energy consumption (US DOE, 2012). In order to reduce this consumption, existing buildings must be retrofit, through replacement or upgrade of their existing building systems, to improve their energy performance. Beyond the energy motivation, a building's operating costs account for the largest portion of the life cycle cost. Thus, deep energy retrofit projects offer an opportunity to significantly reduce both national energy consumption and expenditures. While much research exists on the topic of energy retrofits, very little explores the role of the contractor. This paper explores the contractor's role (rather than the designer's or engineer's role) in delivering deep energy retrofit projects.*

*The contractor plays a critical role in delivering a project that meets the owner's expectations and goals and satisfies the specifications (Ahn and Pearce, 2007). Namely, the contractor executes the plans and specifications, giving physical reality to the design*

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*team's vision. In the case of deep energy retrofits, this role is particularly important, as installation and operation must conform to the design intent to achieve the predicted energy performance. Moreover, the contractor must understand the existing condition to effectively retrofit the building.*

*This paper explores critical building energy efficiency measures and processes for achieving deep energy savings in retrofit projects. Specifically, we present the role of the contractor in a case study project in Phoenix, Arizona where the contractor was engaged in the project early in the design stage. This paper discusses the process of developing and selecting energy efficiency measures (EEMs). It explains the reasons for choosing particular EEMs, including a discussion of selecting an appropriate baseline for energy savings calculations, and documents the impact of EEMs on total energy consumption and design intent. The paper concludes with a discussion of recommendations that, if applied in part or whole, will increase the effectiveness of future construction teams in delivering deep energy retrofit projects.*

## **KEYWORDS**

energy efficiency measures; lean construction; net-zero energy; work structure; retrofitting; deep energy savings; integration; process; collaboration

## **BACKGROUND**

In a design-bid-build environment, the design team releases plans and specifications at the outset of the construction phase, creating a situation where contractors are expected to build without necessarily knowing the owner's project requirements and goals. Late involvement limits the contractor's ability to establish project controls and anticipate probable risks, let alone provide meaningful feedback on constructability. In particular, the contractor is unable to suggest energy efficiency measures (EEMs), nor is (s)he able to analyze the constructability or the cost-effectiveness of the designer's proposed EEMs. Thus, contractors may be responsible for installation, and in some cases, performance of, EEMs without being able to participate in their selection. Further, as a result of late involvement, energy goals may not be communicated well to the contractors (a LEED certification goal is often transparent, but the energy measures required to achieve it may not be). Unclear goals may also hinder the contractor's ability to suggest efficient alternatives.

The authors postulate an integrated project delivery (IPD) environment best promotes deep energy savings. Integrated project delivery (IPD) seeks to improve project outcomes through a collaborative approach of aligning the incentives and goals of the project team through shared risk and reward, early involvement of all parties, and a multiparty agreement (Kent and Becerik-Gerber, 2010). It eliminates major issues associated with late involvement, providing the contractor awareness of the owner's goals and the design team's intent for each EEM. Moreover, this environment allows the contractor to suggest EEMs, as well as the best project approach from a constructability perspective, which may provide a cost advantage to the owner. The contractor may also have ideas about alternative methods to achieve

the owner's project goals. Given the contractor's experience with field conditions and EEM installation, the contractor's suggestions may prove invaluable. Finally, an IPD environment encourages collaboration between the design and construction teams to identify elements of the retrofit project critical to achieving deep energy savings (e.g., (Parrish and Regnier, 2013) and develop practices that increase the effectiveness of the construction team in delivering these energy savings.

## CASE STUDY

### *Project Description*

This paper presents the case of a 1536 m<sup>2</sup> office building retrofit in Phoenix, Arizona. This is an ideal case study project as the general contractor is also the owner—DPR Construction self-performed the work for their own Phoenix office. Though this is not a typical process, it illustrates the value of early contractor involvement through an IPD-like process. While selecting a Phoenix office, DPR knew they wanted to retrofit an existing space rather than build a new space. DPR began this project shortly after finishing construction of their net-zero-energy San Diego office, and sought to apply lessons learned in San Diego on this project. They chose a space in central Phoenix built in 1972, with windows on either side of the building that provided sufficient daylight and ventilation (Blair, 2012).

Similar to the energy goal in San Diego, DPR set a goal of net-zero energy consumption for their Phoenix office at the project outset. (This requires the building produce as much energy as it consumes on an annual basis (Crawley, 2009)). The Phoenix team applied lessons learned in San Diego to achieve net-zero on this project. Specifically, continual focus on the energy goal, staying engaged throughout the process, full resource planning, and follow through were critical for the success of the Phoenix office retrofit. This allowed the Phoenix team to complete the project—from conceptual design through construction—in ten months. DPR worked with several sub-contractors on this project to accomplish the task of saving energy affordably: the project payback period is 7.5 years. Moreover, this project is the first net-zero private office building in Arizona (DPR Review, 2011).

DPR implemented design-build delivery on this project. They used several innovative teaming and delivery practices on the project, though they did not explicitly consider new construction methods. DPR believed that the sub-contractors were very important on this project as the quality of their work determined the effectiveness of EEMs. Hence, proper communication and coordination were vital. Specifically, DPR facilitated an open exchange of information so everyone had all the information they required to complete their work. Moreover, DPR aligned the team around the net-zero energy goal for the project. Lean principles made the construction process very efficient. DPR ensured the right people were in the right place at the right time by requiring all subcontractors be present at regularly scheduled project coordination meetings. Lack of participation results in wasted time and resources, and given that no decision could be made in the absence of even one party, attendance was imperative. Further, DPR required attendance to capture the benefits of complete involvement outlined by Alarcon (2011), including confirmation of assumptions, plan validation, and expedited and improved decision-making. This complete involvement allowed the subcontractors to share their expertise and helped in making the right decisions quickly, which in turn prevented drawing revisions and reduced rework.

### ***Energy Efficiency Measures Employed on this Project***

A broad spectrum of EEMs exists for implementation in energy-efficient commercial building projects. An energy consultant can help a project team select the appropriate measures for the specific project. Often, this selection process comes down to a cost-benefit analysis that compares the initial cost of the EEM to the expected energy savings (both in terms of reduced consumption and reduced utility bills). Typically, EEMs that contribute toward large energy savings address HVAC and daylighting and thus it makes sense to allocate the majority of funds for these measures (DOE, 2010).

Choosing the right EEMs for a retrofit project is certainly critical for achieving required savings; however, developing a baseline for a retrofit project often proves even more critical. A baseline is a model illustrating a building's energy consumption under an assumed set of conditions. Per ASHRAE's non-residential building standard, 90.1 (2007), a baseline building design is a computer representation of a hypothetical design based on the proposed building project. Therefore, it provides a starting point to set energy goals (e.g., save 30% relative to the baseline energy consumption, totalling 85,000 kWh each year), and enables the energy consultant to ensure that the EEMs meet the energy goal and the building performs as required. The energy consultants developed several baselines for DPR's Phoenix office. The energy consultants used Energy Pro software to develop an ASHRAE (ASHRAE, 2007) baseline for LEED certification. Though the ASRAE baseline provided value for LEED certification, a baseline from the San Diego office proved more appropriate for EEM design and performance targets. This baseline supported the zero-net energy concepts and PV sizing.

Per the energy consultant, the suite of EEMs typically considered for office retrofit projects include daylighting and efficient HVAC systems. For this case study, the following EEMs were considered (Rofle, 2013):

- Mixed mode active and passive ventilation
- Enhancing the passive ventilation system by developing a thermal buoyancy driven system
- Enhancing the passive ventilation system by adding passive evaporative cooling
- Floor plan layout to promote passive air flow
- Floor plan layout to reduce heat gain to passive areas by providing active cooling/heating to south and west facades
- 100% daylighting
- Control of plug loads (Vampire switch)
- Thermal solar hot water
- Exterior shading

A cost-benefit analysis helped the project team to select EEMs for this project. The team only considered EEMs with a payback period of 10 years or less. Table 1 lists the EEMs employed on this project. The following sections describe EEMs in greater detail.

### ***Cooling Energy Efficiency Measures***

DPR has designed its systems for average desert climatic conditions. Their office operates a passive ventilation system to the extent possible, and only in extreme conditions does it switch to a mechanical heating and cooling system. It is advisable to design buildings for average climatic conditions, rather than climatic extremes, as the extreme condition likely occurs

**TABLE 1.** Low-Energy Features of the DPR Phoenix Office.

Low energy Feature	Description	Details
Oversized roll-up doors	Operable massive doors which can be rolled up.	3 in number.
Operable windows	Operable windows to let the air flow in, during extreme heat.	87 in number.
Zinc-clad solar chimney	A thermal chimney used to create an updraft of air and improve indoor ventilation.	26.5 m(87-foot) long, 1 in number.
Evaporative cooling shower towers	The hot air moving through the tower is cooled with a shower of water.	4 in number.
Isis® Big Ass Fans®	Circulates the air.	2.4 m diameter, 12 in number.
Sola tubes	Natural source of light, serving the purpose of artificial lighting.	82 in number.
PV-covered canopy covers	Photo-voltaic system to generate solar power.	Over half parking space, 79Wdc.
Vampire shut off switch	A single switch to turn off the plug loads.	To eliminate plug, like computer monitors.
Green screen/Living wall	Living wall of plants meant for external shading.	At North and East of building's perimeter.

infrequently or perhaps never. Further, the layout of the interior space dictates the success of the passive ventilation system. Thus, the layout should promote free air movement (e.g., avoid obstructions such as partition walls) that cools the interior. Oversized roll-up doors and operable windows support this free movement of air, allowing large volumes of outside air to enter the building when outdoor conditions are satisfactory. The design team designed the three EEMs related to cooling (solar chimney, evaporating cooling towers, and Big Ass fans) to work synergistically to cool the interior of the office. To ensure all three EEMs function as intended, DPR may opt to employ Measurement & Verification (M&V) and make adjustments to the EEMs as required based on measured performance.

### ***Solar Chimney (Cooling EEM 1)***

A solar chimney (Figure 1) is an EEM that supports passive ventilation of interior space using metals that heat up to create a stack effect; moreover, the metals reflect light, in turn providing light to interior space. The solar chimney leverages the principles of air movement and negative pressure to passively exhaust air. The solar chimney's exterior side is made of a metal surface. This metal surface heats up and transmits heat to the interior air. The solar chimney also includes operable vents that exhaust this hot air out, and thus control the temperature inside the space. This exhausting of hot air within the chimney creates a vacuum that draws air up from the bottom of the chimney, promoting circulation within the building interior. Solar chimneys work in conjunction with evaporative cooling towers and Big Ass fans and hence, they must be located at the end of the air current. DPR opted for a zinc-clad solar chimney as they had zinc inventory from a previous project. This allowed DPR to pursue both their lean and green goals—they reduced their inventory while promoting energy savings in their new office.



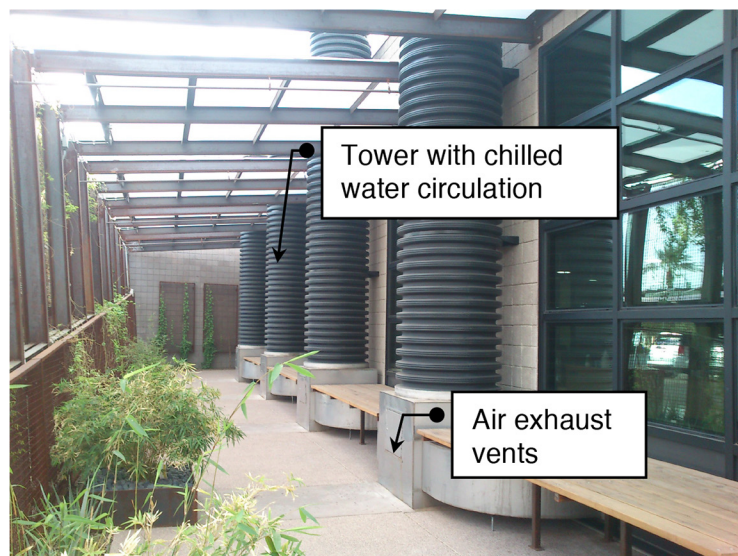
**FIGURE 1.** Solar Chimney  
(Photo by Akash Ladhada,  
10/22/13).



### ***Evaporative Cooling Towers (Cooling EEM 2)***

Evaporative cooling shower towers (Figure 2) are long towers with water showers within that cool incoming hot air. They operate on the principle of heat transfer. The incoming hot air is cooled when the heat is transferred to the chilled water, which is continuously circulated within the tower. The cooled air has a tendency to fall and when it does, the cooled air from the tower is exhausted to the interior office space at the occupant's foot level, the tower bottom. The cooling towers have filters that clean the air before cooling. Similar to other EEMs the number and location is imperative. For greatest efficiency the cooling towers must be arranged perpendicular to the air flow, this supports maximum air flow into the towers. In case of DPR the cooling towers are located on the east façade. Also, the design team located the towers so as not to obstruct the view from the window. Cooling towers work in conjunction with the solar chimney and Big Ass fans, and operable windows and doors complement their function.

**FIGURE 2.** Evaporative Cooling  
Towers (Photo by Akash Ladhada,  
10/22/13).



### ***The Big Ass Fans (Cooling EEM 3)***

The Big Ass fans (Figure 3) are high-volume low-speed fans that maintain airflow at low energy expense. The fan's large blades support generation of air current. The movement of air gives a perceived notion of cooling (Big Ass Fans, 2013). It is important to design the exact location to promote uniform air current and avoid haphazard movement of air, and coordinate the position with other systems to avoid clash. The operable doors and windows (Figure 3) allow large volumes of outside air to enter the office.

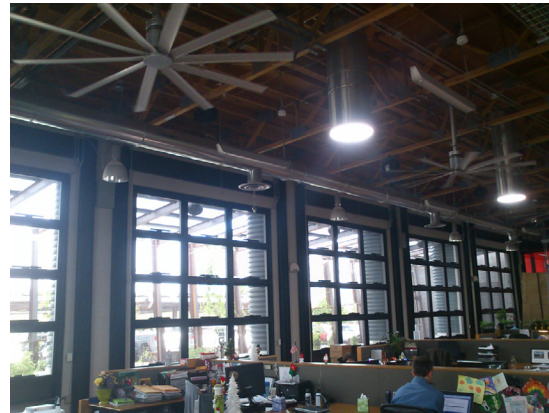
### ***Sola Tubes***

Sola tubes (Figure 4) are an efficient way to light interior space without consuming energy. Sola tubes work on the principle of reflection, capturing sunlight from the rooftop and reflecting it into workspace through a series of mirrors arranged within the tube. The sola tube materials reduce heat transmittance into the building interior, offering daylight with minimal heat gain; thus, the lighting does not increase the load on the building's HVAC system. Sola tubes (Figure 4), function as windows for the interior by providing light only in the region required. Hence, the location of these tubes is critical. Further, according to a technical report by NREL, natural light increases the productivity of people as compared against artificial light. This feature allowed DPR to reduce their lighting power density by installing fewer artificial lights. DPR reduced their lighting energy consumption by 70% due to the combined effect of daylighting, reduced lighting power density, and minimal need for artificial light.

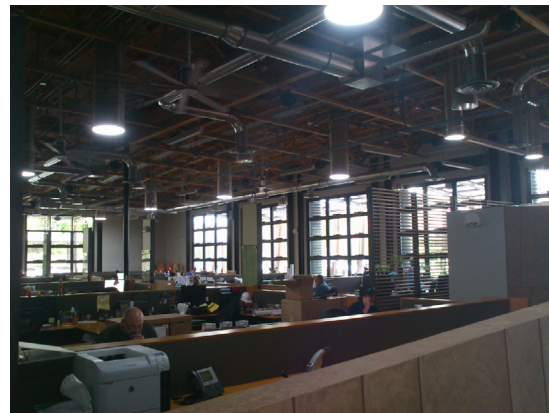
### ***PV-Covered Canopies***

The PV-covered canopies (Figure 5) serve a dual purpose: they provide shade to the cars parked below and the photovoltaic (PV) panels on the roof surface provide a means of renewable energy generation. Note that DPR

**FIGURE 3.** Big Ass Fans (Photo by Akash Ladhada, 10/22/13).



**FIGURE 4.** Sola tubes (Photo by Akash Ladhada, 10/22/13).



**FIGURE 5.** PV-Covered Canopy (Photo by Akash Ladhada, 10/22/13).





installed minimal PV, relying on EEMs to reduce the consumption insofar as possible before offsetting the remainder with onsite renewable energy production, and achieving the building's zero-net energy goal. This approach is uncommon, often designers size PV systems to generate all the energy required by the building without first seeking proper savings.

### ***Vampire Switch***

A Vampire Switch (Figure 6) is a single, manual, easy-to-operate switch. Located near the exit of workplace and wired to all the electrical outlets, this allows the last person leaving the office to shut off power to all outlets so equipment like computer monitors do not draw any power overnight (thus, so-called vampire loads are eliminated). This feature reduced night-time plug load consumption by 90%.

### ***Green Screen (Living Wall)***

For this project, a living wall of plants provides external shading (Figure 7). This wall of hanging plants covers the perimeter of the building. This energy efficiency measure comes at a low cost with manifold benefits. The screen is a good protection against dust and air pollution, letting fresh air into the office while minimizing the pollutants that enter. The screen also cuts off the excessive brightness from the desert sun and keeps the building cool. Finally, it gives the building a nice appearance from the outside and creates a nice ambiance inside by damping the sound of the busy city traffic.

### ***Effectiveness of the EEMs***

The EEMs employed on the case study project not only reduce electricity loads in the building, they contribute to a comfortable, appealing, and pleasant workspace. Table 2 lists the average electricity consumed per day by each building system (DPR Phoenix Dash Board).

**FIGURE 6.** Vampire Switch (Photo by Akash Ladhadd, 10/22/13).



**FIGURE 7.** Green Screen (Photo by DPR, 10/22/13).





**TABLE 2.** Daily Average Energy Consumption for Various Building Systems.

System	Average electricity consumed per day (kW-hours)
Mechanical loads	71
Plug loads	122
Lighting loads	62
Total	255
Net Energy Consumption	28.85 kBtu/sf/year

Note that the office consumes 255 kW-hours of energy on average each day, but it produces 270 kW-hours of solar energy on average each day. Thus, the DPR office is a net-energy producer, producing more energy than it consumes on an average day. Though this paper focuses on energy efficiency, DPR was also conscientious of water efficiency due to the arid desert climate in Phoenix. Ladhani and Parrish IGLC21 (2013) presents the water consumption data.

## LEAN PRACTICES THAT SUPPORT ZERO NET ENERGY RETROFITS

While the teams aligned around the Zero Net Energy (ZNE) goal that led to the EEMs described previously, the team also focused on their design and construction processes to implement lean practices to the extent possible. In the course of this case study, the authors discovered several lean practices that contributed to this project's energy performance. The authors propose these practices be replicated on other retrofit projects, to the extent possible, to promote deep energy savings.

### 1. Learn from Previous Projects

The DPR Phoenix team implemented lessons learned in the course of the San Diego office project as described earlier in this paper. In this project, the Phoenix team placed the solar tubes more efficiently after learning from mistakes in placement at the San Diego office. Similarly, after seeing how much energy the San Diego office consumed at night, the Phoenix team opted to install vampire switches to manage night-time energy consumption. Owners, designers, and contractors should learn from their previous projects and adjust their approach on future projects accordingly. Lessons learned about improving constructability may be of particular importance.

### 2. Install Individual Performance Measuring Systems for each Building System

Separate energy monitoring systems for each building system enable the DPR office building to achieve net-zero energy. All the individual systems in the building have a separate monitoring system that allows the building manager to study the performance of individual systems and adjust those systems performing poorly to reduce their energy consumption. This also allows the building manager to ensure the systems are integrating properly (e.g., a reduction in lighting energy consumption should coincide with a reduction in HVAC energy consumption). Performance measurement at the system level enables energy management at the same level, and is thus a recommended practice for deep energy retrofits. Roth et al. (2006) suggest monitoring systems contribute to energy savings on the order of 20%.

### **3. Develop a Complete Understanding of the Existing Facility**

Contractors and owners should ensure they have a complete understanding of the existing facility as the existing conditions may not reflect what is shown on the drawings. A laser scan of DPR office revealed that the building was 8 inches longer than what was represented in the drawings. Had this gone undiscovered in the design phase, it could have affected the layout of the office interiors and would have resulted in rework. Similarly, a full examination of DPR's office confirmed existing insulation was sufficient. Understanding the current condition before beginning the retrofit allows contractors and owners to better plan the project and reduce the risk of redundant spending.

### **4. Conduct Value Analysis**

Preplanning forms a major part of early involvement and encompasses the process of value analysis (Gibson et al., 1995). Preplanning and set-based design (e.g., Parrish et al. 2007) help to look into different options available and price each option early in the project. The process of value analysis helped DPR identify six different systems that enabled net-zero energy consumption and suited the project. This furnished options for the decision makers to choose from. This process helps the construction team determine several options, analyze their life cycle cost, and determine their payback periods. This process also enumerates the benefits of a particular measure while simultaneously assessing its first cost, its life cycle cost, and its payback period. On DPR's project, this process revealed the ideal payback period is eight to ten years. This payback period allows the project team to include EEMs with relatively high initial cost and relatively low maintenance costs. On the one hand, if the payback period was lower, then high-first-cost EEMs would essentially not be considered, despite relatively low maintenance costs. On the other hand, if the payback period is higher, it is unlikely an EEM will prove a good investment.

### **5. Involve the Project Team Early and Often**

We have discussed the benefits of early involvement throughout this paper. However, a few important reasons for early involvement of the project team bear re-mentioning. Specifically, designers and contractors should support owners. Designers and contractors should share their expertise to help the owner make the right decision. Contractors and subcontractors in particular can drive the project and prevent rework if they provide constructability input and allow the project to benefit from their experience and lessons learned from previous projects. Further, the project team can examine design assumptions and adjust them as appropriate to meet the project's needs.

### **6. Lean Principles as a Foundation for Management**

DPR implemented management methods on this project that ensured the team was aware of the whole project, rather than simply a specific trade. Thus, team members were able to understand how their work fit into the entire project and how their individual work integrated and interfaced with that of other contractors. DPR pursued lean principles and adopted lean tools, like Last Planner (Ballard, 2000), map-days, and just-in-time delivery. These lean principles fostered communication and shared understanding amongst team members. Last Planner and map-day scheduling (or reverse-phase scheduling) continually reinforced the role of each

subcontractor, as well as DPR, on the project, resulting in a more coordinated schedule and project approach. Finally, practices like just-in-time delivery resulted in a clean site, promoting productivity, safety, and efficiency.

### ***7. Involve an Energy Consultant***

To achieve deep energy savings, an energy consultant should be a member of the project team. Early involvement gives the energy consultant time to understand the project and suggest and design appropriate energy efficiency measures. Though the owner provides the project goal, the energy consultant and the contractor assume the responsibility for operationalizing the goal. We argue this is not only appropriate, but a best practice, as the energy consultant and contractor each have expertise that allows them to achieve the owner's goal. Typically, the energy consultant develops several alternative suites of EEMs and presents them to the owner and contractor. This presentation provides the owner the information required to select the best suite of EEMs based on benefits, life cycle cost, payback period, constructability, or a combination thereof.

### ***8. Challenge Engineering Design Assumptions***

Design teams make assumptions on most projects. These assumptions often reflect the design team's experience, understanding of the project, and industry norms. Whatever the basis, engineering assumptions often pertain to worst-case scenarios. However, in the case of energy performance, the worst-case scenario (all loads in the building achieving maximum at the same time), is highly unlikely and may not be detrimental to business practices enough to warrant the cost of prevention. If a project team can articulate an acceptable level of risk, the owner, design team, and contractor team can "right size" building systems and significantly reduce energy consumption.

### ***9. Conduct Measurement and Verification (M&V) Analysis***

The performance of EEMs may improve if building operators implement measurement and verification during the operation phase. Measurement of performance and energy consumption during the operation phase allows the facility manager to understand what adjustments may be required to facilitate optimal EEM performance and ensure that EEMs work synergistically. This synergistic approach to energy efficiency results in increased energy savings. The data collected can be stored and used as reference for future projects, as exemplified by DPR's San Diego office, which provided the baseline for the Phoenix office. Also, the performance and energy consumption can be verified against the design intent to ensure the building is operating as designed, or if it is not, that building operators understand why it is not doing so. DPR has a system that captures energy consumption and generation data, a Lucid Dashboard (<http://buildingdashboard.net/dpr/#/dpr>). While this system allows building users to "see" how their building is performing, DPR does not use this system or its energy data to verify design intent or to make adjustments to individual EEMs. Finally, M&V allows building owners to understand the effectiveness of the EEMs implemented, as they compare pre- and post-retrofit energy consumption to determine energy savings for various building systems or the building as a whole.

## CONCLUSIONS

This paper is based on a case study of a net-zero office building, located in Phoenix, Arizona. The owner and the contractor were the same on this project and the contractor drove the project right from the beginning. Though not typical, this case study reveals several elements that were critical to the project's success, i.e., achieving the goal of net-zero, that could be implemented on other IPD projects. Based on this case study, the authors developed recommendations for future retrofit projects with a goal of deep energy savings.

To achieve net-zero energy consumption, the design team must first focus on efficiency, making the building consume as little as possible to reduce the required energy production. When selecting EEMs for a project, the project team's understanding of the existing building and climate conditions is critical. A deep energy retrofit depends on selecting EEMs that will offer both cost and energy benefits. Climatic conditions and the existing building's end use profiles illustrate those building systems that offer the greatest opportunities for savings (e.g., cooling systems in hot, dry climates). The project team must implement EEMs that address the largest energy users as these EEMs offer the greatest benefit for the cost invested. For example, DPR understood the climatic conditions in Phoenix and identified that the largest energy user was the HVAC system. Hence, the project team implemented passive ventilation systems to address this large load. Where possible, implementing passive solutions is often most cost-effective, as these solutions offer large energy reductions.

Another key to reducing energy demand is to question design assumptions. Often, design teams size building systems for coincident peak loads, when all systems must address the worst case loading. However, in reality, this is an extremely unlikely event. Thus, systems may be designed for "typical" conditions and safety measures implemented for worst case scenarios. For example, DPR implemented oversized roll-up doors and operable windows to flush the building with outside air in the event that the passive systems were not drawing in enough outside air. Finally, the energy production system should be sized to offset only the remaining energy demand.

The authors argue that process improvements during retrofit design and construction are as important as implementing measures that directly impact energy consumption. Projects may be plagued by lack of alignment between the design, construction, and owner teams about the project goals. Though this lack of alignment manifests itself in different ways, dissatisfaction is often a result. In particular, the owners may be dissatisfied with the final product if it does not meet their goals. Thus, owners need to understand their energy needs and set the project goals accordingly (Holloway and Parrish, 2013) and the project lead should seek goal alignment across teams at the project outset. The owner team will most likely accept this responsibility, though the owner team may state the project goals in terms of certification (e.g., LEED certification), energy savings goals (e.g., net-zero), or another means, rather than an absolute energy consumption target (e.g., 20 kBtu/square foot/year). The project delivery team may need to work with the owner team and provide education about relative costs and benefits of various EEMs, and analyse this data to determine the best EEMs for the retrofit project.

Contractors have many responsibilities in deep energy retrofit projects. They help in detailing the project, identifying and delivering cost savings, and coordinating subcontractors. However, arguably the most important responsibility the contractor has in a deep energy retrofit project is providing constructability input. If contractors provide constructability information to designers and owners at the project outset, they can support improved decision-making. Further, contractors can and should help the owner to clearly define the



project objectives based on their construction expertise. Finally, the contractor can help the owner to define project needs based on the objectives (e.g., if the objective is net-zero energy consumption, the project needs daylighting). These project objectives provide a true basis for design, and may allow the project delivery team to re-visit and adjust typical design assumptions, generally used for worst-case scenarios.

Finally, when considering optimization of the project delivery process, the design and contractor teams should establish collaboration and communication protocols that promote optimizing the project as a whole and foster a team environment. Both the contractor and design teams should collaborate to make recommendations to the owner that provide value. Lessons learned from previous projects can and should be leveraged by the project team, as these can help to develop and select efficiency measures appropriate for the building's size, function, and location. If each project team member focuses on meeting the project goals, rather than goals of individual team members, the likelihood of success, in terms of energy performance and other metrics, improves.

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