1.4. Net Zero Retrofit Optimization

Purpose

The high level purpose of the net zero retrofit optimization was to demonstrate the feasibility of achieving net zero energy performance within the constraints of a retrofit construction project. Considerable analysis has been done on lifecycle cost-based integrated design for commercial new construction. However, retrofit projects have a number of unique constraints that limit the applicability of many new construction integrated design best practices. The Fort Carson net zero retrofit optimization was designed to characterize the aspects of retrofit projects that make them unique, and build a framework around that characterization that would allow retrofit project teams to accurately analyze retrofit efficiency packages from a lifecycle cost perspective.

Research Question

What set of efficiency solutions are available at the optimal energy cost lifecycle for common retrofits?

Building 1219—an office building that had been retrofitted from former barracks at Fort Carson—was used as the reference point for this analysis. Efficiency measure selection and design recommendations were tailored to the basic architectural characteristics of Building 1219 (size, shape, orientation, existing exterior constructions, etc.). By building the analysis around Building 1219, we ensured that outcomes from the retrofit analysis could be used to inform future Fort Carson renovations (particularly for the campus buildings similar to Building 1219).

We did not explicitly model the Building 1219 retrofit. The reference, or baseline, model for this analysis was designed to capture the fundamental characteristics of Building 1219 (geometry, space types, layout, use patterns, etc.), as well as the minimum performance requirements of ASHRAE Standard 90.1-2007. Accordingly, we did not incorporate any

Building 1219 retrofit strategies (Light Emitting Diode [LED] lighting, high efficiency boilers, etc.) into the baseline model that go beyond the minimum requirements of the ASHRAE Standard. However, we did use the Building 1219 retrofit strategies as a starting point for the development of a high efficiency retrofit package; many of the candidate efficiency measures for our optimization analysis align closely with measures currently implemented in Building 1219. In cases where candidate efficiency measures were modeled after implemented retrofit strategies, we detail that relationship and explain any recommended modifications.

The Fort Carson net zero retrofit optimization was designed to analyze retrofit efficiency packages from a lifecycle cost perspective.

Methods

The following subsections detail the methodology used to construct and execute the Fort Carson net zero retrofit optimization. There are two key aspects to the methodology:

1. the design methodology used to select candidate efficiency measures; and
2. the simulation methodology used to evaluate the candidate efficiency measures and present the results of that analysis from a lifecycle cost perspective.

Design Methodology

Accounting for Retrofit Constraints

First and foremost, we limited our analysis to efficiency measures appropriate for a retrofit project. Retrofit projects are typically constrained in a number of ways, including:

1. **Footprint.** An existing building's basic shape and orientation are more or less fixed. Any serious modifications to shape and orientation would likely fall under the category of new construction. In a new construction scenario, a building's shape and orientation can be specified to maximize the benefits of many efficiency measures (passive solar design, daylighting, heating, ventilation, and air conditioning [HVAC] design, etc.). Accordingly, the potential benefit of certain efficiency measures may be limited in a retrofit scenario due to shape and orientation constraints.

2. **Exterior Constructions.** These include exterior wall constructions, roof constructions, and fenestration constructions, as well as fenestration placement. While it may be possible to completely replace existing exterior constructions in a retrofit scenario, it is much more likely that existing constructions would be modified (adding-on as opposed to replacing). Window construction replacement is relatively noninvasive and may make sense in certain scenarios (however, it will be much more expensive to replace windows in a retrofit scenario than in a new construction scenario, where there are no removal costs and window construction upgrades can be evaluated using incremental costs). Window size or placement modifications are much less likely (as they would require significant modification to the existing exterior wall constructions). Again, these constraints can affect the potential impact of a number of efficiency measures (e.g., daylighting).

Candidate Efficiency Measures

For our analysis, we designed candidate efficiency measures to account for these practical constraints. We also emphasized efficiency solutions that are simple and passive (require limited facility manager or occupant intervention, minimize long-term maintenance requirements, do not rely on complicated controls, etc.). We believe this to be good design practice in general, but even more important for retrofit scenarios, where retrofit technologies and strategies need to work within the framework established by the existing building design (construction, layout, systems, etc.). Many of the candidate efficiency strategies are modeled after strategies that were employed in the renovation of Building 1219. Candidate efficiency measures are described below. Measure costs properly account for the construction constraints (e.g., existing equipment removal and disposal) of a retrofit scenario. Much of our measure cost data came from equipment manufacturers, equipment distributors, or RS Means. Other costs were estimated by industry experts (HVAC) or National Renewable Energy Laboratory's (NREL's) in-house technology experts (lighting, plug loads). The detailed performance and cost assumptions that NREL used to develop candidate efficiency measures for modeling is provided in Appendix C.

Candidate efficiency measures were designed to account for practical constraints

1. **Lighting Power Density (LPD) Reduction.** Lighting equipment replacement is a proven retrofit measure. We considered two LPD reduction scenarios: (1) replacing existing fluorescent fixtures with 36W LED fixtures (corresponding to an LPD of 0.58 W/ft2); (2) replacing existing fluorescent fixtures with 24W LED fixtures and then supplementing the ambient fixture output with 6W LED workstation task lights (corresponding to an LPD of approximately 0.40 W/ft2). Building 1219 was retrofit with LED lighting technology, but with higher wattage fixtures and tighter grouping (resulting in an LPD of around 0.75 W/ft2).

2. **Improved Lighting Controls.** Upgrading lighting controls is also a common retrofit strategy, especially in cases where control upgrades are combined with the replacement of existing lighting equipment. We considered two lighting control improvements: (1) adding vacancy sensors to enclosed offices to turn off lights when spaces are unoccupied; (2) designing lighting (egress base lighting and vacancy sensor-controlled primary ambient lighting) in common areas to take advantage of the fact that the vast majority of tasks completed in those areas (corridors; open conference and printer areas between enclosed offices) require only low levels of light. The Building 1219 retrofit controls the lighting for open conference and printer areas using occupancy sensors. This strategy ensures that lights are off at night when the building is unoccupied but does not take advantage of the fact that most occupants do not need the full ambient lighting when passing through those spaces.

3. **Daylighting Open Offices.** Depending on building orientation, daylighting can also be a popular retrofit strategy (again, especially in cases where it is combined with other lighting retrofits). We considered daylighting for all open office areas (including large open conference rooms) with direct access to daylight through existing fenestration (all such spaces in Building 1219 meet this criterion). The impact of daylighting depends heavily on the commissioning process (verification of control strategies and tuning of set points contribute heavily to system performance); accordingly, commissioning makes up a substantial portion of our estimated cost for implementing daylighting. The Building 1219 retrofit utilizes dimming ballasts and photosensor-controlled daylighting in open conference rooms; however, its impact is limited by the design of the system (sensor placement, in particular).

4. **Plug Load Reduction and Controls.** Plug load reduction and controls are also very common retrofit measures (plug load equipment is typically purchased as new in retrofit scenarios). We considered three plug load reduction and control measures: (1) opting for controllable plug strips (which turn off automatically after 11 hours of use) over standard plug strips for all office workstations (this measure is equivalent to the office plug load control strategy currently utilized in Building 1219); (2) opting for high

efficiency computing equipment (mini desktops and high efficiency LED monitors) over standard efficiency equivalents; (3) reducing support equipment (printers, scanners, fax machines, elevators, etc.) plug load density by 25%. For the support equipment power reduction strategy, we conservatively assigned a whole-building budget of $50,000. In reality, however, there are many strategies that can be employed to make this a low- or no-cost measure (replacing multiple pieces of equipment with multi-function units; consolidating office support equipment [including eliminating redundant equipment at individual workstations]).

5. **Envelope Improvements.** We identified a set of envelope measures that work within the practical constraints imposed by the existing envelope of Building 1219 (prior to retrofit). As mentioned previously, many envelope improvements may not be practical in a retrofit scenario (from both cost and construction standpoints). Appropriate strategies are likely to be project dependent. However, our proposed strategies are built around conservative assumptions (existing exterior wall and roof constructions cannot be replaced; windows can be replaced but not resized or relocated). We considered four envelope improvement strategies: (1) adding exterior roof insulation and a white roof membrane (on top of the existing roof construction, as was done for the Building 1219 retrofit); (2) adding spray foam insulation to the interior side of exterior walls (which requires the exterior wall construction be finished with drywall on the interior side); (3) adding window insulation modules to the interior of existing window constructions to reduce heat transfer and infiltration; (4) replacing existing windows with electrochromic windows (a strategy that eliminates the need for window shades, which rely on occupant interaction to positively impact building energy consumption).

6. **HVAC Modification.** We considered a single, holistic, HVAC improvement: replacing the baseline HVAC system with ground source heat pumps (GSHPs) for conditioning and a dedicated outside air system (DOAS) for ventilation. This type of system can reduce long-term maintenance costs substantially. Additionally, decoupling conditioning equipment from ventilation equipment can result in substantial energy

savings. Key requirements for making this technology cost-effective are building load reduction and right-sizing of HVAC components. Higher capacity supplemental equipment (fluid cooler, boiler, etc.) may be required in very unbalanced climates (very hot or very cold).

7. **Renewable Generation.** As the goal of the analysis is to achieve net zero energy performance (on-building, as opposed to on-site or off-site, if possible), all building energy use not eliminated through efficiency improvements needs to be offset by renewable energy generation. For the purposes of this analysis, we assume that all renewable energy is generated by photovoltaic (PV) arrays. PV generation is a simple, passive strategy that can be applied successfully in most climates.

Simulation Methodology

The primary requirement of the simulation methodology for the Fort Carson net zero retrofit optimization was to make the overall analysis as replicable as possible. Accordingly, we utilized only publically available modeling tools (SketchUp [http://www.sketchup.com/] and the OpenStudio suite of modeling tools [http://openstudio.nrel.gov/]) to execute our analysis. We also prioritized tools (such as the Match Photo capability of SketchUp, which allows building geometry to be defined using a set of photos that map out the building exterior) that reduce the amount of existing information required to model a building. NREL has created a YouTube channel (http://www.youtube.com/user/NRELOpenStudio/) for OpenStudio that provides users with a wealth of up-to-date tutorial videos that cover all aspects of the OpenStudio tool suite (covering topics relevant to this analysis such as: creating geometry using Match Photo; modeling from imported plans and elevations; creating geometry with the OpenStudio plug-in for Sketchup; specifying model inputs using the OpenStudio application). The following steps define the simulation methodology that we applied to this analysis.

Only publically available modeling tools were used in the analysis.

1. **Create the Baseline Model.** The first step in the simulation process was to create a baseline energy model. As mentioned previously, we modeled Building 1219. To accurately capture the characteristics of Building 1219, as well as demonstrate the capabilities of SketchUp (Match Photo, in particular) and OpenStudio, we modeled Building 1219 through the following approach:

a. *Specify Exterior Geometry with Match Photo*. SketchUp has a capability known as Match Photo, which allows users to specify the geometry of a building solely using photos of the exterior of the building. During a site visit to Building 1219, we took a series of photos that fully captured the exterior wall geometry of Building 1219 and then used Match Photo to build the exterior geometry for the model of Building 1219. Match Photo is particularly useful for capturing elevations and exterior shading objects (trees, bushes, etc.); see Figure 42 for a visual of the Match Photo process.

Figure 42 Specify exterior geometry using Match Photo

b. *Adjust Geometry Using Building Floor Plans*. In this particular case, we had access to detailed floor plans for Building 1219. We took advantage of that resource by importing those plans into SketchUp and then using them as a reference point to make subtle adjustments to the geometry created using Match Photo (Figure 43). While using Match Photo does not require a user to have building floor plans, we were able to use them to improve the accuracy of the model geometry. In theory, we could have used the floor plans to specify the building outline and then used Match Photo only to specify relevant elevations, heights, and fenestration placement. However, one of our goals for this project was to demonstrate the capabilities of the simulation tools.

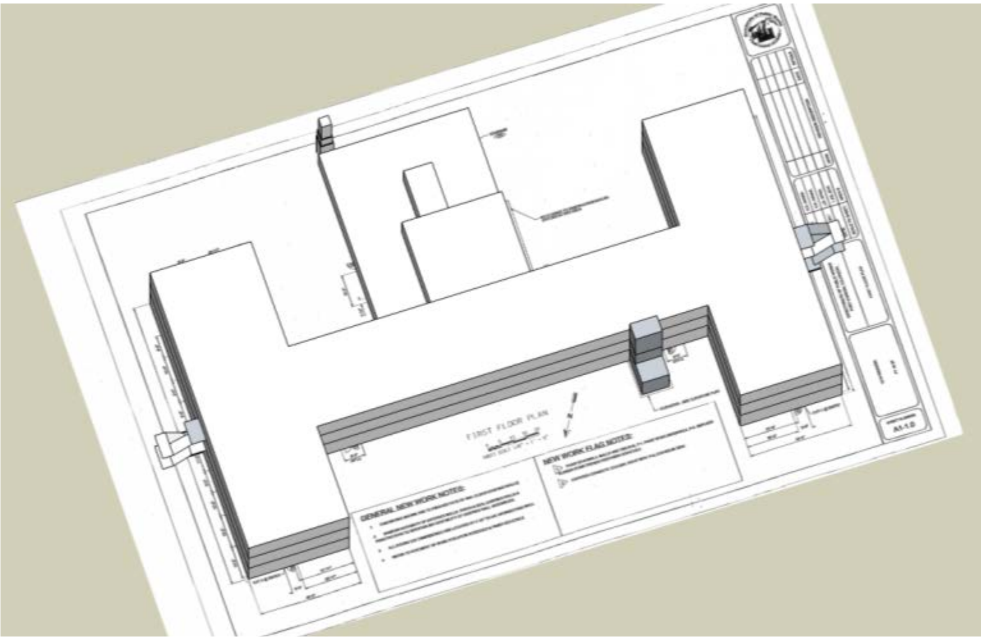


Figure 43 Adjust exterior geometry using building floor plans

c. *Specify Interior Geometry Using Building Floor Plans*. Next we specified Building 1219’s interior geometry using the building floor plans (aligning the floor plan with the geometry for the appropriate floor and then tracing out interior zone boundaries onto the model geometry). This could be done without building plans (though likely requiring some estimation), but having the plans made the process much faster and more accurate; see Figure 44 for a visual.

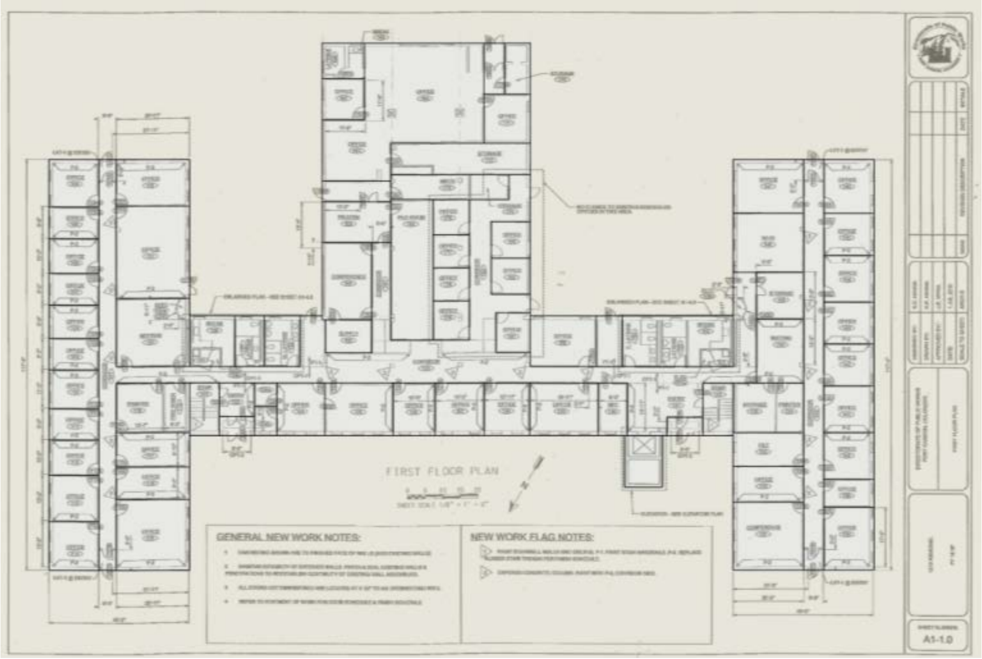


Figure 44 Specify interior geometry using building floor plans

d. *Use SketchUp Geometry As a Template for the Creation of An OpenStudio Model*. Once the SketchUp geometry was finalized, we used it as a template for the creation of OpenStudio spaces, the basic building blocks of an OpenStudio model. The OpenStudio plug-in for SketchUp allows users to create OpenStudio spaces by extruding SketchUp geometry into three dimensions (converting 2-D geometry to 3-D by specifying a height). Once spaces were created, we grouped them into logical thermal zones (e.g., combining two adjacent restroom spaces into a single thermal zone). We also converted the SketchUp geometry for overhangs, staircases, chimneys, trees, and shrubs into OpenStudio shading objects.

For this analysis, we did not lump together spaces (neither adjacent spaces of different types nor spaces of the same type distributed throughout the building); we modeled each space where it exists in the actual building. While this does add accuracy to the model, it also increases the complexity of the model as well as the time it takes to run. As mentioned previously, much of our workflow was determined by our goal of demonstrating simulation tool capabilities. For a typical analysis, we try to simplify models wherever possible (space lumping, simplified perimeter geometry, banded windows versus punched windows, etc.) to save analysis time.

e. *Use Building Operational Data to Specify Modeling Inputs*. After creating OpenStudio geometry, we used data collected during our Fort Carson site visit and through submetering to specify modeling inputs (internal gains, schedules, etc.). Where Building 1219 data were lacking, we specified building operational schedules according to typical schedules we have developed for past modeling efforts.

f. *Apply ASHRAE 90.1-2007 to Establish Baseline Performance*. Because we wanted to capture a baseline for building performance corresponding to code-minimum requirements, we applied ASHRAE Standard 90.1-2007 to the models to specify many other aspects of the energy model (HVAC system type, roof insulation, window properties, etc.). To ensure that our baseline model did not deviate too significantly from the characteristics of Building 1219, we bypassed 90.1 requirements in certain cases where they differed noticeably from Building 1219 characteristics (e.g., exterior walls, which are largely un-insulated in Building 1219).

2. **Write OpenStudio Measures.** The next step was to specify the inputs required to model our set of candidate efficiency measures and build those requirements into OpenStudio measures, which can be applied as perturbations to OpenStudio models to simulate the energy savings impacts of efficiency measures. OpenStudio measures are sets of programmatic instructions (such as an Excel macro) that make changes to an energy model to reflect their application. Measures can be written specifically for an individual model, or they may be more generic to work on a wide range of possible models; NREL has developed a guide to provide users with detailed instructions on how to write OpenStudio Energy Conservation Measures (http://openstudio.nrel.gov/openstudio-measure-writing-guide). We wrote OpenStudio measures for the majority of the efficiency strategies described in the Design Methodology section (and in more detail in Appendix C). Note that measures often need to be written with other measures in mind. Will a measure work correctly when applied in combination with other measures? This concept is important to remember when writing measures.

3. **Write EnergyPlus (IDF) Measures.** While the goal is to develop OpenStudio to the point that it supports all EnergyPlus modeling objects, that goal is not yet a reality. In certain cases, EnergyPlus objects do not have OpenStudio equivalents. To perturb those EnergyPlus objects for the application of an efficiency strategy, it is necessary to write IDF measures. IDF measures are very similar to OpenStudio measures; the only difference is that they are written to perturb EnergyPlus objects directly (as opposed to modifying OpenStudio objects that are later converted to EnergyPlus objects). Through necessity, we wrote IDF measures for efficiency strategies not currently supported by OpenStudio (ground source heat pumps, electrochromic windows, and PV generation). To clarify, the simulation workflow is as follows:

a. OpenStudio measures are applied to the OpenStudio model.

b. The OpenStudio model is converted to an EnergyPlus IDF file.

   c. IDF measures are applied to the IDF file.

   d. The IDF file is simulated using the EnergyPlus engine.

4. **Write a Script to Identify an Optimal Package of Retrofit Strategies.** There are multiple approaches to applying efficiency strategies to a baseline model. For this analysis we applied strategies using a sequential search algorithm, which mathematically optimizes a solution space according to primary and secondary objective functions. For our analysis, we chose incremental lifecycle cost and building energy use as the primary and secondary objective functions, respectively. What this means is that we used a mathematical algorithm to identify the package of efficiency solutions that results in the lowest lifecycle cost (which factors in first costs, energy cost savings, maintenance costs, replacement costs, analysis period, and discount rate) for a given level of building energy performance. The specifics of this approach are described in more detail in the Optimization Results section.

We wrote a Ruby script that used OpenStudio methods to assemble (through the application of our OpenStudio and IDF measures) optimized packages of efficiency strategies according to the output of the sequential search algorithm (with the objective functions described previously, as well as an analysis period of 20 years and a real discount rate of 2.3%). To analyze the cost-performance tradeoff associated with efficiency measure application, we assigned incremental costs (capital, maintenance, and replacement) to each measure (note that certain incremental costs, such as operations and maintenance (O&M) costs for LED lighting, were negative). To broaden the application of the analysis results, and for consistency throughout the Fort Carson project as a whole, energy models were simulated using national average utility rates. Figure 45 shows the final energy model, complete with exterior shading objects and PV panels covering 75% of the roof area, imported into its actual geographic location in Google Earth.

Currently, this type of optimization analysis can only be achieved through Ruby scripting and expert knowledge of the OpenStudio tool suite (users can develop the necessary understanding of OpenStudio at the sub-project, class, and method levels through exploration of the OpenStudio software development kit documentation [http://openstudio.nrel.gov/latest-c-sdk-documentation]). Recent releases of the OpenStudio tool suite have added user interface-based parametric analysis functionality through the Parametric Analysis Tool (PAT). While PAT does not currently support optimization analysis, it does allow users to apply and analyze specified combinations of OpenStudio measures; NREL has developed a series of tutorials to guide users through the PAT analysis process (http://openstudio.nrel.gov/parametric-analysis-tool-tutorials).

Results and Lessons Learned

The following subsections present the results of the net zero retrofit optimization and highlight key lessons learned throughout the process.

Optimization Results

The baseline model, specified to be minimally compliant with ASHRAE Standard 90.1-2007, was the starting point for the optimization. For this analysis, the baseline energy performance was approximately 73 kBtu/ft^2·yr, which is typical for an average office building. As a point of reference, Spectra Tech's analysis calculated baseline energy performance of 68 kBtu/ft^2·yr and retrofit performance (corresponding to the actual Building 1219 retrofit package) of 58 kBtu/ft^2·yr (corresponding to energy savings of approximately 15%).

To build lifecycle cost-optimized efficiency packages, candidate efficiency measures were applied as perturbations to the baseline models. The sequential search algorithm applies perturbations in groups we call iterations. During the first iteration, each measure is applied to the baseline and simulated independently. The algorithm then selects the mathematically optimal point for the given objective functions. For our analysis, the objective functions were incremental lifecycle cost (primary) and building energy use (secondary). Given these objective functions, the search algorithm searches for the lowest lifecycle cost package starting from the baseline model, and proceeding to packages with lower and lower energy use. Figure 46 shows the baseline point and the data points from the first iteration; the selected package from the first iteration was the baseline model perturbed with the common area lighting control measure.

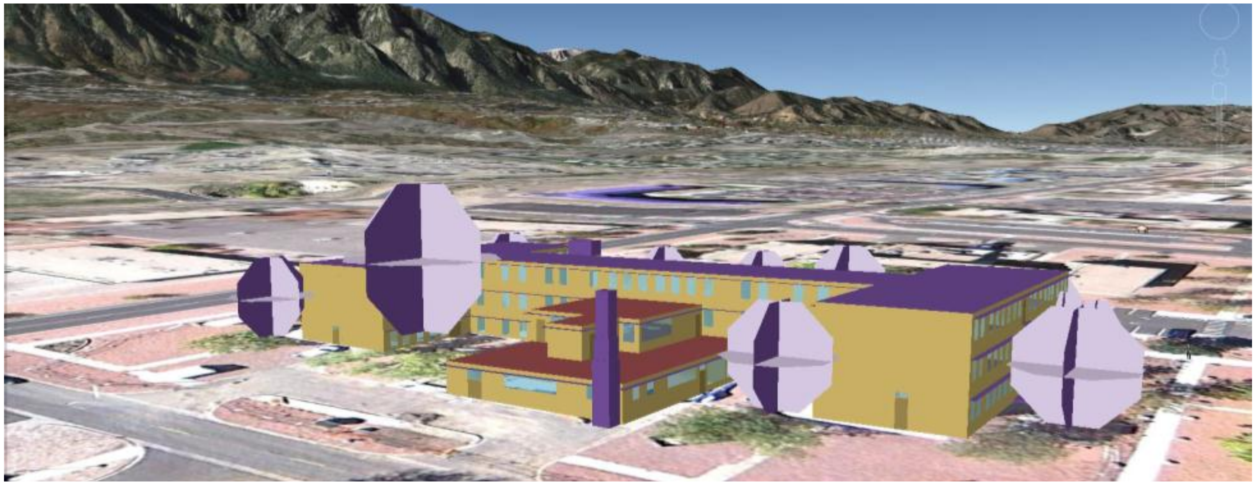


Figure 45 Final energy model in Google Earth with PV and shading objects

Once the most optimal package from the first iteration is selected, that package becomes the starting point for the second iteration. Once again, all packages that are single-measure perturbations of the iteration starting package are simulated (in this case, one of those perturbations would remove the measure selected in the first iteration, recreating the baseline; because that package would have already been simulated at the outset of the analysis, it would not be simulated again). After completion of the simulations for the second iteration, the search algorithm determines the most optimal package from within that group; that new optimal package then becomes the starting point for the next iteration. This process continues until the algorithm can no longer find a package with lower energy use (or lifecycle cost) than the selected package from the previous iteration. Figure 47 shows the results of the first four iterations of the Fort Carson net zero retrofit optimization; note that a plus sign indicates that the selected package is an addition to the previous package (as opposed to a subtraction, which occurs when a measure is removed).

Figure 46 shows the final results of the optimization, and describes a number of key packages:

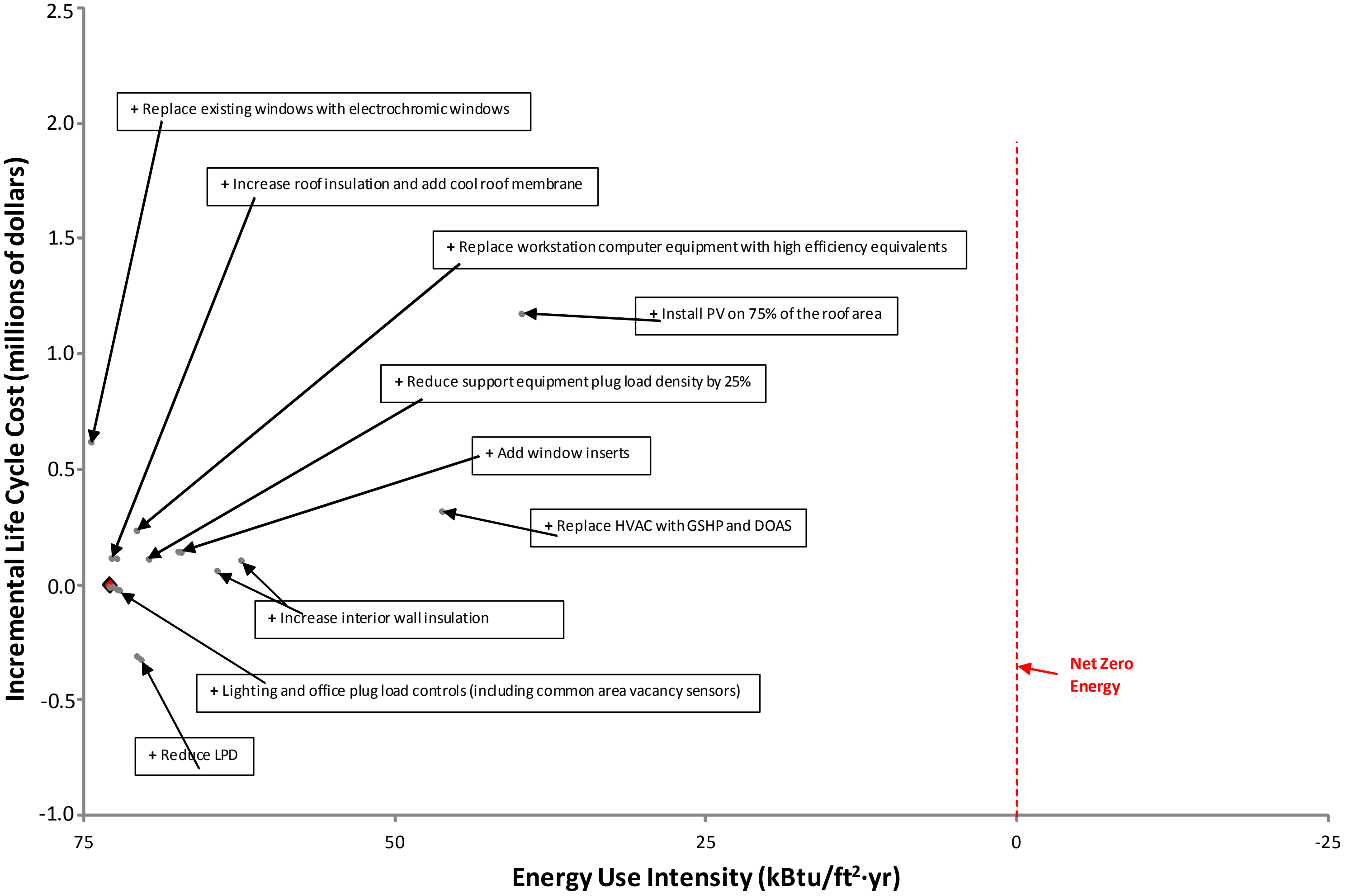


Figure 46 Baseline model and first iteration of perturbations

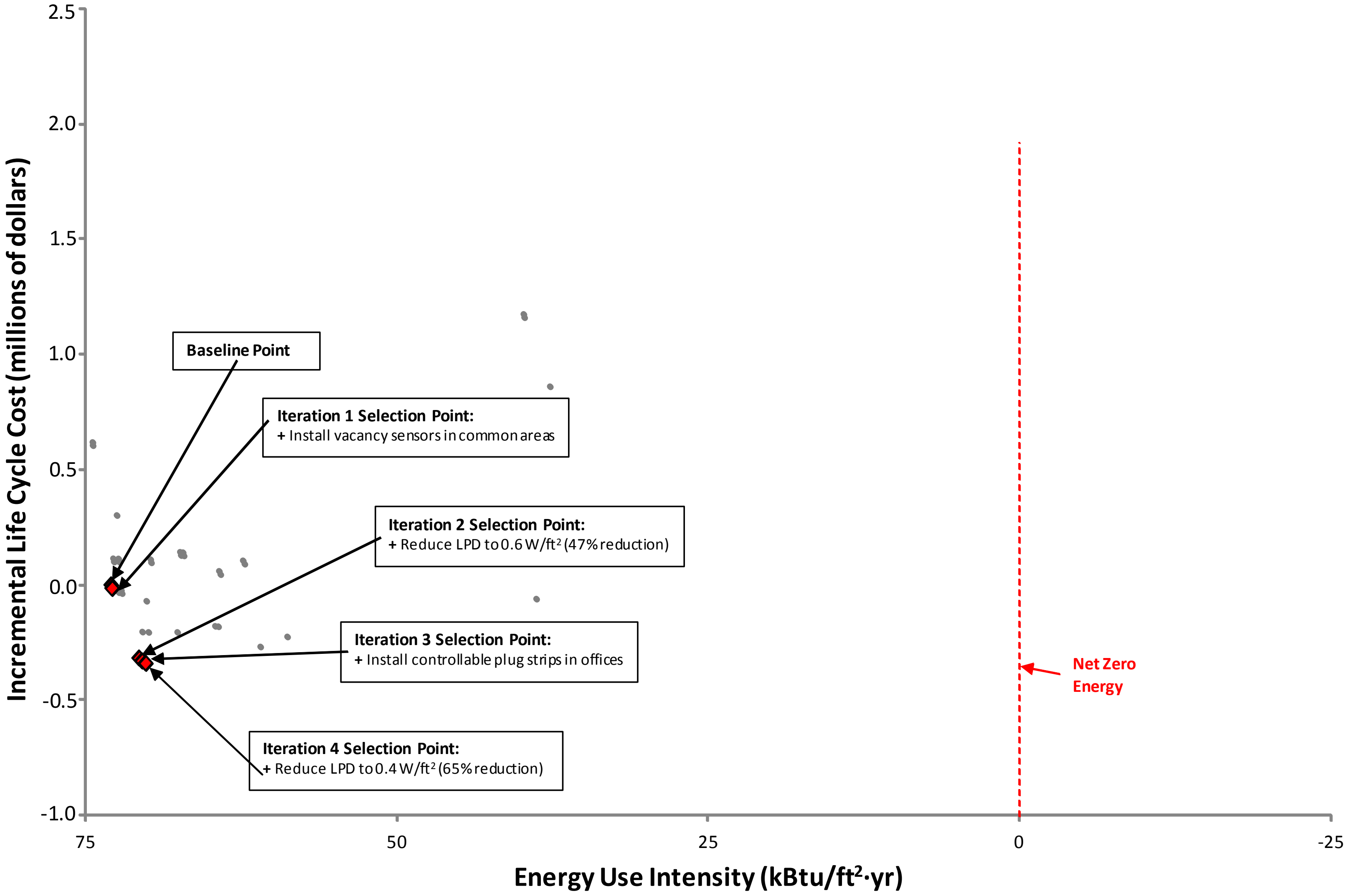
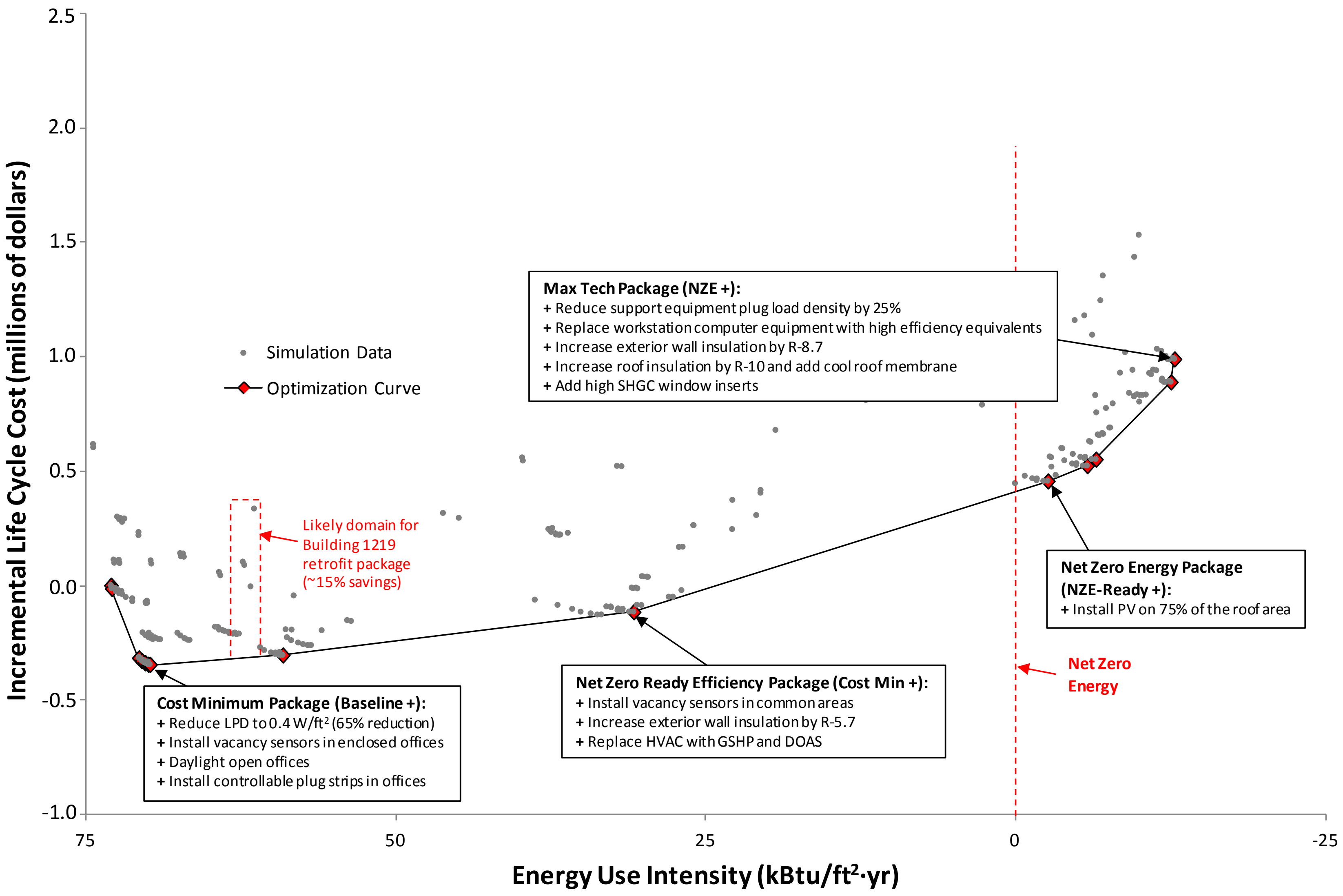


Figure 47 Results of first four iterations (with selected packages highlighted)



Max Tech Package (NZE +):
+ Reduce support equipment plug load density by 25%
+ Replace workstation computer equipment with high efficiency equivalents
+ Increase exterior wall insulation by R-8.7
+ Increase roof insulation by R-10 and add cool roof membrane
+ Add high SHGC window inserts

Likely domain for Building 1219 retrofit package (~15% savings)

Net Zero Energy Package (NZE-Ready +):
+ Install PV on 75% of the roof area

Cost Minimum Package (Baseline +):
+ Reduce LPD to 0.4 W/ft² (65% reduction)
+ Install vacancy sensors in enclosed offices
+ Daylight open offices
+ Install controllable plug strips in offices

Net Zero Ready Efficiency Package (Cost Min +):
+ Install vacancy sensors in common areas
+ Increase exterior wall insulation by R-5.7
+ Replace HVAC with GSHP and DOAS

Figure 48 Final optimization results (with descriptions of notable packages)

1. **Cost Minimum Package.** This is the package with the lowest total lifecycle cost (in this case, the most negative incremental lifecycle cost). The cost minimum package results in the best return on investment for the given analysis period (20 years). Note, however, that the energy savings associated with the cost minimum package are quite small (less than 5%). There are many other packages that save considerably more energy and still represent cost-effective investments.

2. **Net Zero Ready Efficiency Package.** We define an efficiency package as being net zero ready when all efficiency measures that are more cost-effective (from a lifecycle cost perspective) than renewable generation have been applied. For this analysis, the net zero ready package resulted in 58% energy savings (corresponding to an energy use intensity [EUI] of 30.9 kBtu/ft2·yr, which is indicative of a high performance office building) at a net reduction in lifecycle cost when compared to the baseline model (indicating that this package is cost-effective for the given economic criteria). The net zero ready efficiency package contains the following key strategies:

a. GSHP with DOAS HVAC system.

b. LPD reduction (to 0.4 W/ft^2, a 65% reduction from baseline lighting levels).

c. Improved lighting controls (vacancy sensors in enclosed offices and common areas).

d. Daylighting of open office and conference spaces.

e. Controllable plug strips (which turn off automatically after 11 hours) for office workstations.

f. Increased exterior wall insulation (by R-5.7).

3. **Net Zero Energy Package.** The net zero energy package is achieved by adding renewable generation to the net zero ready package until net zero annual energy performance is achieved. In this case, net zero annual energy performance was achieved solely with on-building renewable generation (assuming photovoltaic [PV] panels could be installed on 75% of the existing roof area). Note that our analysis assumed direct purchase of the PV system, resulting in a net zero energy solution with a higher lifecycle cost than the baseline model. However, incentives or alternative financing strategies (e.g., power purchase agreements) could improve the economics of renewable generation.

4. **Max Tech Package.** This is the package that achieves the best possible energy performance, regardless of cost. For our analysis, the max tech package includes the most aggressive possible package of candidate efficiency measures and the maximum practical amount of on-building PV generation. The max tech package (without renewable generation) achieved an EUI of 20.7 kBtu/ft2·yr, which is comparable to that for NREL's Research Support Facility (not counting the energy use of the shared data center).

Lessons Learned

Throughout the Fort Carson net zero retrofit optimization analysis, we emphasized the importance of defining a process that is effective, straightforward, and replicable. Accordingly, we utilized only publically available modeling tools (SketchUp, the OpenStudio suite of modeling tools) and prioritized tools (Match Photo) that reduce the amount of existing information required to model a building. In this section, we highlight the key lessons learned in defining this process and applying it to a real building. Note that this was the first project for which we were able to utilize these simulation tools to this extent for a real building.

The net zero ready package resulted in 58% energy savings at a net reduction in lifecycle cost

1. **Balancing Model Fidelity with Available Time and Resources.** As mentioned previously, one of our goals for this project was to demonstrate the capabilities of the simulation tools. Accordingly, we modeled Building 1219 in great detail. An alternative approach would be to simplify the model in a number of key ways (lumping spaces together to reduce the number of thermal zones, replacing punched windows with banded windows, simplifying or eliminating shading objects, etc.). If done correctly, this can greatly reduce the time and effort needed to build and simulate the model without significantly impacting its accuracy. This is a well-known modeling tradeoff that is not unique to this analysis; however, it is worth mentioning from a replication standpoint.

2. **Using Match Photo.** For this analysis, we primarily used Match Photo to specify the exterior geometry of the model. Match Photo is a powerful tool that allows users to accurately capture the geometry of a building with nothing more than a camera. In cases where building plans may not be available, using Match Photo (and/or Google Earth, which in most cases could be used to establish a rough footprint of a building) to establish building geometry is likely to be the most effective approach. However, it is much simpler and faster to build a model from documented dimensions than to try to capture those dimensions using Match Photo. In cases where other building data is available, Match Photo should be used sparingly (ideally, only to capture dimensions that are otherwise undocumented).

3. **Using OpenStudio.** OpenStudio is a powerful suite of modeling tools. In the recent past, the OpenStudio development team has made great strides in making its capabilities user friendly (developing a software application [OpenStudio App] and resource database [Building Component Library] that allow users to build energy models through a download, drag, and drop approach, as well as a parametric analysis tool (PAT) that provides users with an interface through which they can apply and evaluate the results of efficiency strategies). That being said, there is still a significant scripting component to performing an energy modeling analysis using OpenStudio (especially when analysis needs to be tailored to a specific project); efficiency measure definition and sequential search optimization currently require scripting. When planning

to use the OpenStudio tools, it is important to take this into account and ensure that the proper project resources and expertise are available.

Recommendations

The following subsections detail NREL's recommendations, both to Fort Carson in particular and to GSA in general.

Fort Carson Recommendations

The retrofit analysis is most directly applicable to future retrofit of Fort Carson barracks buildings with the same basic characteristics as Building 1219; however, the recommended strategies should be applicable to office building retrofits in general. Applicability of recommended strategies to other Fort Carson building types (DFAC, TEMF, etc.) will depend on the extent to which those building types share characteristics with typical office buildings. While the exact packages that result in the lowest lifecycle costs at each level of energy performance will be somewhat building- and climate-specific (note that we only performed the optimization for Fort Carson, Colorado, not for any other locations), we believe that the majority of the proposed efficiency measures (especially the lighting and plug load measures, all of which are very common for office new construction and retrofit projects) should at least be considered in an office retrofit scenario. As we mentioned previously, we focused on proven measures that are simple and passive. By prioritizing efficiency strategies with a high probability of success (in particular, those for which success is not highly dependent on the behavior of facility personnel and/or building occupants), long-term, campus-wide return on retrofit investment can be maximized.

Note that many of the candidate efficiency strategies have already been incorporated to some extent in the Building 1219 retrofit, including:

- LED lighting

- Controllable plug strips for office workstations
- Zone level HVAC (fan coil units)
- High efficiency computer monitors
- Multifunction office support equipment
- Sensor-based lighting control, including daylighting
- Additional roof insulation and white roof membrane
- Renewable generation (solar water heating)

In that way, our recommendations build on the incorporation of efficiency into the Building 1219 retrofit to reach a higher tier of cost-effective retrofit performance. An integrated design approach to efficiency strategy selection (as embodied by our optimization analysis), as opposed to a like-for-like approach, is critical for maximizing energy performance in retrofit scenarios.

GSA Recommendations

A key focus of our analysis was to document the simulation process and highlight opportunities for replication across GSA and throughout the commercial building sector at large. Given the necessary expertise, NREL's analysis can be fully replicated. The simulation tools (SketchUp, OpenStudio) we used to execute our analysis are publically available. Additionally, much of the project workflow is aided by guided user interfaces that make the simulation tools more accessible and user friendly. Some aspects of the analysis required scripting capabilities and more detailed knowledge of the OpenStudio tool suite. However, some of those barriers can be mitigated through generalization. The Building Component Library (BCL) (https://bcl.nrel.gov/) provides many resources (OpenStudio measures, building constructions, operating schedules, etc.) that can help streamline project workflows and in some cases reduce the need for scripting. If generalized analysis will suffice, the required energy modeling expertise will be reduced (but certainly not eliminated). The more project-specific the analysis needs to be, the more in-depth knowledge of energy modeling, scripting, and the OpenStudio tool suite will be required.

Additionally, we believe the simple, passive efficiency strategies that we analyzed for the Building 1219 retrofit optimization, along with the integrated design approach that we applied to efficiency package selection, have wide applicability to office buildings across the commercial building sector. While the optimization package results are specific to Fort Carson and to Building 1219, we recommend considering the candidate efficiency strategies (especially the lighting and plug load strategies) for office retrofits throughout GSA's portfolio.

The simple, passive efficiency strategies identified in this retrofit optimization have wide applicability to office buildings across the commercial sector.

Appendix C Retrofit Efficiency Measure Detailed Assumptions

Lighting Measures:

1. Reduce Lighting Power Density (LPD)

- Apply to whole building (office lighting equipment will dominate the building; ignore the fact that not all spaces will be lit by the same type of fixture).
- **Baseline:** assume 1.1 W/ft^2 (according to ASHRAE 90.1-2007 limit for offices), provided by 2x2 fluorescent fixtures with four 17W lamps at a contractor cost of $131 per fixture ($187.14 per fixture assuming a contractor markdown of 30%). At 68W per fixture, each fixture should cover an area of 61.8 ft^2 to result in an LPD of 1.1 W/ft^2. Area normalized fixture cost for the baseline case is $3.03/ft^2 (see costing assumptions below for fixture spacing).
- Costing assumptions:
  i. Assume the same fixture spacing (one per 61.8 ft2) for all lighting scenarios. Base system costs purely on fixture costs unless otherwise noted (assume all other costs are the same regardless of lighting fixture).
  ii. All fixtures are assumed to be 2x2 (both fluorescent and Light Emitting Diode [LED]), for consistency.
  iii. Account for the incremental operations and maintenance (O&M) cost associated with installing LED fixtures rather than fluorescent fixtures (assume O&M costs are the same for both LED LPD reduction scenarios). Assume baseline fluorescent lamps would have a rated life of 30,000 hrs but an actual average life of 20,000

hrs; fluorescent lamp life is significantly affected by on/off cycling and many other sources estimate fluorescent lamp life at 10,000 hrs or even less. Assume LED lamps have a life of 70,000 hrs (the lamp for the fixture used to cost LED lighting for this measure is rated for 50,000 hrs to L80 [the industry standard for LED useful life is L70, indicating the lamps would last longer than 50,000 hrs]; other sources indicate that LED lamps can last to 100,000 hrs or more). Assume that fluorescent replacement bulbs cost $4 each ($16 per fixture, for this case [4 lamps per fixture]) and that it takes 15 minutes (0.25 hrs @ $70/hr [RS Means labor rate] = $17.50) to replace the lamps in each fixture (other sources estimate 30 minutes per lamp; our assumption is more in line with group re-lamping). Assume that fluorescent ballasts must be replaced every other re-lamping cycle at a cost of $115 per fixture ($45 for parts and $70 for labor [1 hr @ $70/hr]). Assume that fluorescent fixtures must be replaced every four re-lamping cycles at a cost of $187.14 per fixture and $140 for labor (2 hrs @ $70/hr) Assume that the cost of LED lamp replacement is half of the fixture cost (assuming an average fixture cost for the two LPD reduction strategies of $315.29 results in a per fixture re-lamping cost of $157.64) and that this cost covers fixture replacement as well (in reality, some LED fixtures will require full fixture replacement for re-lamping whereas others will allow for the replacement of individual LED modules , at a significantly reduced cost; our assumption is meant to represent an average case). Assuming that LED lamp replacement takes 1 hour, labor for re-lamping would be $70/fixture (the same as that for ballast replacement, based on the assumption that it would require more work than simple fluorescent tube replacement). These assumptions result in per fixture O&M costs of $8.64/1000 hrs and $3.25/1000 hrs for fluorescent and LED lighting fixtures, respectively. Assuming 4,560.4 lighting hrs per year (neglecting any schedule changes or daylighting strategies that may be applied during the optimization) and 61.8 ft2 per fixture, this results in annual O&M costs of $0.64/ft2·yr and $0.24/ft2·yr for fluorescent and LED lighting fixtures, respectively.

- **LPD Reduction 1:** reduce fixture wattage from 68W to 36W (2x2 LED fixture), resulting in an LPD of 0.58 W/ft^2 (47% reduction).

   i. Contractor cost is $240 per fixture ($324.86 per fixture assuming a contractor markdown of 30%). Area normalized fixture cost is $5.26/ft2 (incremental cost above baseline is $2.23/ft2).

   ii. Assume lighting design is required for this low LPD scenario (primarily for fixture selection). Lighting design costs are taken from a Whole Foods Commercial Building Partnership (CBP) project, for which the lighting design fee was $10k. Assume the fee is flat and not area dependent. Also assume that some minimal lighting design (provided by the fixture manufacturer and/or the project lighting contractor) is required for the baseline scenario, at 25% of the cost of expert lighting design (the Whole Foods case). So the incremental cost for lighting design is $7,500 for the building (Building 1219 has a floor area of $49,000 ft2, resulting in an area normalized lighting design cost of $0.15/ft2).

   iii. Combining the incremental fixture cost ($2.23/ft2) and the incremental lighting design cost ($0.15/ft2), the total incremental cost for this measure is $2.38/ft2.

- **LPD Reduction 2:** reduce fixture wattage from 68W to 24W (2x2 LED fixture), resulting in an overhead lighting LPD of 0.39 W/ft^2 (a 65% reduction). Assume that task lights will need to be added at the workstations due to the lower lighting levels. According to estimates made from the Building 1219 floor plan, the average floor area per enclosed office workstation is 166.7 ft^2. That increases to 244.8 ft^2 per open office workstation.

   i. Task light data for the Research Support Facility (RSF) was used as a reference point. Assume that each task light has 6W of lighting power and costs $225. The LPD added to the enclosed office and open office space types should be 0.04 W/ft^2 (at \$1.35/ft^2) and 0.02 W/ft^2 (at \$0.92/ft^2). So an LPD of 0.43 W/ft^2 (61% reduction) should be applied to enclosed offices, an LPD of 0.41 W/ft^2 (63% reduction) should be applied to open offices, and a 65% LPD reduction should be applied to all other spaces.

   ii. Contractor cost is $214 per fixture ($305.71 per fixture assuming a contractor markdown of 30%). Area normalized fixture cost is \$4.95/ft^2 (incremental cost above baseline is \$1.92/ft^2)

iii. Again assume an incremental lighting design cost of $7,500 ($0.15/ft^2) is required for this scenario. Assume that the lighting design expertise and effort is the same for both LPD reduction strategies, and that the different in LPD is a matter of personal preference on the part of the building owner.

iv. Combining the incremental fixture cost ($1.92/ft^2), the incremental task light cost ($1.35/ft^2 for enclosed offices, $0.92/ft^2 for open offices, and $0 for all other space types), and the incremental lighting design cost ($0.15/ft^2), the total incremental cost for this measure is $3.42/ft^2 for enclosed offices, $2.99/ft^2 for open offices, and $2.07/ft^2 for all other space types.

2. Add Vacancy Sensors to Enclosed Offices

- Apply only to enclosed offices.
- Model during unoccupied hours using an adjustment to the night schedule (reduce night time LPD fraction from 0.2 to 0.05). Model during occupied hours using on/off daylighting control with a daylight threshold of 300 lux; basically, assume that occupants will turn the light on if the daylight level decreases below 300 lux, but would otherwise leave the light off.
- Base incremental costs for this measure on the cost required to add network control functionality to the lighting system. Assume that Building 1219 has the most basic of lighting control systems in the baseline scenario ($0.12/ft^2 for basic lighting timer control for a 50 zone system, according to RS Means). Use the RSF lighting control system as a reference case for the cost of advanced lighting control. The RSF cost for lighting controls is $0.98/ft^2. The RSF lighting system is more complex than most commercial lighting systems; assume a 25% cost premium is associated with that additional level of complexity, resulting in a typical advanced lighting control cost of $0.74/ft^2. Thus, the incremental lighting control cost for this measure is $0.62/ft^2.
- Because 90.1-2007 requires occupancy sensors for enclosed offices, assume that the costs associated with occupancy sensors and vacancy sensors cancel out.

3. Light Common Areas with a Combination of Egress Lighting and Vacancy-Sensor Controlled Primary Lighting

    - Apply this measure to the following space types: Common and Corridor.

    - Assume an egress lighting level of 0.1 W/ft^2. Base the incremental cost of egress lighting on the cost of the additional wiring that would be required to control it separately from the rest of the overhead lighting. According to RS Means, this cost amounts to \$0.20/ft^2.

    - Incremental cost for adding vacancy sensors is again assumed to be the cost associated with adding advanced lighting control capabilities, \$0.62/ft^2.

    - This measure will be modeled with a schedule modification. The modification will be different for corridors and common areas. RSF data indicate that, for spaces where lights may or may not be turned on depending on the task being performed (break room, printer room, etc.), the average fraction of installed lighting power that is used during occupancy is 30% (or, more simply, that, during occupancy, the lights are turned on 30% of the time and off 70% of the time). Assume the average power of the "off state" during occupied hours is 0.1 W/ft^2 (9% of the installed lighting power). Accordingly, the average power fraction of the corridor lighting system during occupancy is 0.36 (assuming 30% "on" and 70% "off"). The baseline lighting fraction at max occupancy is 0.9; 0.36 is 40% of that value. To model this measure for corridors, the existing lighting schedule fractions will be multiplied by 40% during occupied hours. For common areas, which are used as meeting rooms, assume (conservatively) that the lights are turned on 50% of the time. Accordingly, the average power fraction of the common space lighting systems during occupancy is 0.55. The baseline lighting fraction at max occupancy is 0.9; 0.55 is 61% of that value. To model this measure for common spaces, the existing lighting schedule fractions will be multiplied by 61% during occupied hours. For both corridors and common spaces, the lighting fraction schedules will be set to 0.05 during unoccupied hours (assuming vacancy sensors keep lights totally off, but assuming conservatively that all spaces have some minimum usage throughout the night to account for security, random occupancy, etc.).

- Total incremental measure cost is $0.82/ft^2

4. Daylight Open Offices

- Apply this measure only to open office space types (all open office spaces in Building 1219 have access to daylight).
- Assume a daylighting set point of 300 lux and continuous dimming. Assume continuous dimming down to 0% power.
- Assume daylighting can be facilitated with dimming ballasts, photosensors, and the necessary wiring and controls; assume no light louvers or other such equipment is needed.
- Assume a $10 fixture up-charge (conservative), resulting in a cost increase of $0.16/ft^2 to the lighting system.
- Approximate the rest of the cost for the daylighting system using the cost to commission and control it. It took a commissioning agent two weeks to commission the daylighting system for the RSF. Assuming 80 hours of total labor at $100/hr, this resulted in a cost of $8,000. Assume that the daylighting commissioning cost is largely fixed (not very floor area dependent). The total cost of the RSF lighting system was $2.2 million. Typical commissioning costs for an entire lighting system are on the order of 1%, or roughly $22,000 for the case of the RSF. This points to the fact that daylighting commissioning made up 36% of the lighting system commissioning cost, which seems reasonable. For Building 1219, the $8,000 daylighting commissioning cost can be area normalized to $0.16/ft^2
- Assume the cost of adding daylight control is the same as the cost of adding advanced lighting control, $0.62/ft^2
- Total incremental measure cost is $0.94/ft^2.

Plug Load Measures:

1. 11 Hour Plug Strip

- Apply this measure to Open Offices and Enclosed Offices.

- It is possible that this measure could be applied to equipment printer rooms (and common rooms, where such spaces double as printer rooms), break rooms, and meeting rooms, but it is unclear exactly how this would work. Would it be reasonable to have to activate the power strip in a printer room before it could be printed to each morning? Could a fax machine be turned completely off at any given time? What kitchen equipment could be plugged into the power strip and what fraction of the load would that make up? Obviously, a refrigerator could not. For a microwave, it might be possible, but the clock would be reset each morning. For simplicity, assume for now that the measure is applied only to office spaces.

- Currently plug load equipment share the same schedule. In reality, plug load schedules differ by space type. Network Enterprise Center (NEC) plug loads should be on an always on schedule. Printer rooms, common rooms, and break rooms should be on the modified Large Office TSD schedule (set to 30% of the peak daytime value [power fraction of 0.27] at night, to match Building 1219 measured data).

- Assume that current Building 1219 measured data for enclosed and open office plug loads reflect the benefits of installing the 11 hour controllable plug strips. Measured data indicate that such loads are reduced to 30% of the peak daytime value at night. Assume that such loads would be reduced to only 50% of the peak daytime value at night for the baseline case (with standard plug strips). To model this measure, create a modified version of the current baseline plug load schedule (increasing the night time plug load fraction from 30% to 50% of the peak daytime value [corresponding to a power fraction of 0.45]) and apply that schedule to the enclosed and open office space types. Then apply the measure only to the plug load schedules for those space types. This measure should not be applied to discrete plug loads, regardless of the spaces in which they are located.

- Assume that the incremental cost of the measure is \$20 per plug strip (assuming \$10 for a standard plug strip and \$30 for the 11 hour controllable version). Assuming 166.7 ft^2 per enclosed office workstation and 244.8 ft^2 per open office workstation, this amounts to an area normalized incremental cost of \$0.12/ft^2 for enclosed offices, and \$0.08/ft^2 for open offices.

2. High Efficiency Computer Equipment

- Apply this measure to open offices and enclosed offices.
- For the baseline case, assume 100W per desktop computer (at \$450 each) and 37.5W per monitor (totaling 75 W per workstation and \$340, assuming two monitors per workstation at \$170 each). This amounts to 175W and \$790 per workstation: 1.13 W/ft^2 for enclosed offices and 0.71 W/ft^2 for open offices.
- For the low energy case, assume 16.7W per mini desktop (at \$829 each) and 16.5W per monitor (totaling 33 W per workstation and \$580, assuming two monitors per workstation at \$290 each). This amounts to 50W and \$1409 per workstation: 0.30 W/ft^2 for enclosed offices and 0.20 W/ft^2 for open offices (71.4% reduction in each case); at an incremental cost of \$3.71/ft^2 for enclosed offices and \$2.53/ft^2 for open offices.

Envelope Measures:

1. Add Roof Insulation and Replace Roof Membrane

- Apply measure to entire roof.
- Add insulation layer and membrane layer to the top of the existing roof construction.

- Baseline roof construction has R-20 c.i. The Advanced Energy Design Guide (AEDG) recommendation for climate zone 5 is R-30 c.i. We will model two instances of roof insulation addition: one at R-25 c.i. and one at R-30 c.i. For each case, polyisocyanurate materials of the appropriate thicknesses will be added to the baseline model, for access by the OS measure. A roof membrane material will also be added to the model (with cool roof surface properties), to be used by both instances of the roof insulation measure.

- Costs assume that the insulation and new membrane can be added to the top of the existing construction. RS Means cost for placing new membrane over existing: $482.22/100 ft^2 ($4.82/ft^2).

- Assume that the cost of insulation needs to be added. Cost to install 2" of perlite insulation is $1.70/ft^2 (RS Means Assemblies Costs for the same insulation are $1.51/ft^2; accordingly, apply 170/151 cost adjustment multiplier to RS Means Assemblies Costs for polyisocyanurate insulation). The adjusted cost for R-5 c.i. insulation is $1.00/ft^2; the adjusted cost for R-10 c.i. is $1.12. Accordingly, the cost of the insulation layers that need to be added to the baseline roof to hit R-25 c.i. and R-30 c.i. are $1.00/ft^2 and $1.12/ft^2, respectively.

- Total cost for improving the roof insulation from R-20 c.i. to R-25 c.i. and R-30 c.i. is $5.82/ft^2 and $5.94/ft^2, respectively.

- Assume no improvement in infiltration occurs with application of this measure.

2. Add Spray Foam Insulation on Interior of Exterior Wall Constructions

    - Apply to all exterior wall constructions.

    - Add an insulation layer (insulation and steel studs in parallel) and a gypsum board layer to the inside of the existing exterior wall construction.

- Baseline exterior wall construction has R-11.4 c.i. (replace existing baseline construction, which is incorrect, with the 90.1-2007 construction for Climate Zone 4B). The AEDG recommendation for climate zone 5 is R-13.3 c.i. We will model two instances of exterior wall insulation addition: one that assumes that a 1-5/8” metal stud framed wall is filled with polyurethane spray foam (R-4.8 per inch [the average value reported in a Building Green reference], at a density of 48.1 kg/m^3 and a specific heat of 1465.4 J/kg·K [0.35 Btu/lb·°F]); and one that assumes that a 3-5/8” metal stud framed wall is filled with polyurethane spray foam. In both cases the interior surface is finished with 5/8” gypsum board. For the stud spacing, 24” O.C. is assumed. The basic wall construction costs are \$2.15/ft^2 and \$2.25/ft^2 for the 1-5/8” and 3-5/8” cases, respectively. The effective insulating properties of the added constructions were calculated according to Example 5 on p. 27.5 of the 2009 ASHRAE Fundamentals handbook. R-values for each construction were calculated according to both the parallel-flow and isothermal planes methods and then averaged (the handbook indicates that the true value is bounded by the parallel-flow and isothermal planes methods). The resultant effective R-values were R-5.74 (R-5.18 for the insulating layer) and R-8.67 (R-8.11 for the insulating layer) for the 1-5/8” and 3-5/8” cases, respectively.

- Assuming an 8” area fraction for the steel stud material and a steel density of 7,833 kg/m^3, the resultant density of the overall insulating (combined steel and insulation) layer is 670.9 kg/m^3. Assuming a steel specific heat of 502.4 J/kg·K (0.12 Btu/lb·°F), the resultant specific heat of the overall insulating layer is 565.2 J/kg·K (0.14 Btu/lb·°F). Set the absorption properties to those of the insulation (use polyisocyanurate as a proxy for the spray foam).

- To model this measure, three materials will be added to the baseline model for access by the OS measure: (1) a 5/8” gypsum board material, (2) a 1-5/8” steel stud and insulation layer, and (3) a 3-5/8” steel stud and insulation layer.

- A local spray foam installer priced filling a 3-1/2” wall at \$1.10/board ft (assume 0.92 board ft per ft^2 of wall area, according to the area fraction assumption for the steel studs, resulting in a cost of \$3.67/ft^2 for filling a 3-

5/8” wall). RS Means data indicates that filling a 1-5/8” wall would cost roughly half as much as filling a 3-5/8” wall, or \$1.83/ft^2.

- The total cost for this measure is \$3.98/ft^2 of exterior wall area for the 1-5/8” case, and \$5.92/ft^2 of exterior wall area for the 3-5/8” case.
- Assume that this measure reduces building infiltration by 25%. Assume baseline infiltration rates are in line with those for pre- and post-1980 construction from the reference building model set.

3. Add Window Inserts to Reduce Heat Transfer and Infiltration

- Apply this measure to all exterior window constructions.
- Windows are modeled using Simple Glazing Systems. To apply measure, replace baseline Simple Glazing System.
- Make sure that baseline Simple Glazing System construction meets the 90.1-2007 minimum requirements.
- Two instances of the measure will be modeled: a high solar gain instance and a low solar gain instance. Product data was taken from the iWindow web page (for the iWindow 5; iWindow 7 was not considered due to its thickness). First, both the low solar gain and high solar gain constructions (iWindow 5, 0.5” air gap) described on the web page (where the baseline window construction was ¼” single pane clear glazing) were recreated (properties were matched) in EnergyPlus. Then, the single pane, clear construction was replaced with the 90.1-2007 baseline glazing construction for Climate Zone 5B and new properties were calculated. The resultant properties are as follows: U-0.876, SHGC-0.270, and VLT-0.388 for the low solar heat gain case; U-0.850, SHGC-0.240, and VLT-0.347 for the low solar heat gain case.

- Measure cost is the cost of purchasing and installing the window inserts; the manufacturer estimates the total installed cost for the iWindow 5 product at \$30/ft^2 of window area.

- Assume that this measure reduces building infiltration by 25%. Assume baseline infiltration rates are in line with those for pre- and post-1980 construction from the reference building model set.

4. Replace Windows with Electrochromic Windows

- Apply this measure to all exterior windows (this measure and the window insert measure are mutually exclusive; this measure cannot be combined with the window insert measure).

- Modeling this measure requires the addition of two EnergyPlus objects per existing glazing surface: (1) a WindowProperty:ShadingControl object, where Shading Type = SwitchableGlazing, ConstructionWithShadingName is the name of the glazing construction “dark” state, and ShadingControlType = OnIfHighSolarOnWindow; (2) a Simple Glazing System construction that defines the “dark” state for the electrochromic window. The default window construction should reflect the properties of the “light” state for the electrochromic window. For simplicity, assume that the “light” state corresponds to the properties of the baseline glazing construction (U-0.55, SHGC-0.4, and VT-0.508).

- The “dark” state has the following properties: U-0.55, SHGC-0.097, and VT-0.0335.

- To apply this measure, all windows will have to be replaced. According to RS Means, the average replacement cost for a 3 ft x 5 ft window in a three-story building is \$71.12/ft^2 of window area. SAGE estimates that electrochromic windows cost \$27/ft^2 (\$35/ft^2 for the window construction plus \$2/ft^2 for additional installation requirements less \$10/ft^2 for eliminating the need for window shades) more than typical double pane glazing systems. Accordingly, the total cost associated with this measure is \$98.12/ft^2.

- Assume that this measure reduces building infiltration by 25%. Assume baseline infiltration rates are in line with those for pre- and post-1980 construction from the reference building model set.

Heating, Ventilation, and Air Conditioning (HVAC) Measure:

1. Replace Baseline HVAC System with ground source heat pump (GSHP) and dedicated outdoor air system (DOAS) High Efficiency System

- Apply this measure to the entire building using a ruby script that specifies IDF substitutions (this will NOT be an OS measure).

- Ensure that low energy HVAC schedules are applicable.

- Assume that the baseline four pipe fan coil system costs approximately \$25/ft^2, and that the system cost is completely independent of system size.

- GSHP with DOAS systems typically cost \$25/ft^2, including approximately \$5/ft^2 for well drilling. Assume that \$20/ft^2 is fixed (not sizing dependent) and that the well drilling cost scales with system size.

- The peak cooling load measured for the RSF is approximately 80 kW. Assuming a safety factor of 1.2, and a COP of 7.8, this amounts to an installed cooling capacity of 748.8 kW, or 212.9 tons. Given that the RSF has a floor area of 225,000 ft^2, this results in a sizing metric of 1,057 ft^2/ton of cooling capacity. Assuming well drilling costs approximately \$5/ft^2 for a building at this efficiency level, we calculate a capacity-normalized drilling cost of \$5,284/ton.

- Assume 500 ft^2/ton of cooling capacity for the baseline case (typical efficiency). For Building 1219 (49,000 ft^2) this would result in an installed cooling capacity of 98 tons. Cost for a GSHP and DOAS system of this capacity would be \$30.57/ft^2

- Assume 1,000 ft^2/ton of cooling capacity for a high efficiency case (compare to 1,057 ton/ft^2 for the RSF and even more for the RSFII). For Building 1219 (49,000 ft^2) this would result in an installed cooling capacity of 49 tons. Cost for a GSHP and DOAS system of this capacity would be \$25.28/ft^2, or roughly the cost of the baseline four pipe fan coil system. Note that a system capacity of 49 tons would amount to approximately a 39% reduction in system size for Building 1219 (currently equipped with 80 tons of cooling capacity).

- A lifecycle cost analysis by the Oregon Institute of Technology (for National Renewable Energy Laboratory [NREL]) indicates that the annual maintenance cost of a (peak load) 22 ton GSHP system is \$1,899. Assuming a sizing safety factor of 1.2, the annual O&M cost would be \$71.93/ton of cooling. The same analysis indicates that annual maintenance for a similarly sized baseline system (packaged rooftop units with DX cooling and gas furnace heating) would be \$4,476, or \$169.55/ton of cooling (a factor of roughly 2.4 larger than that for the GSHP system). The building floor area for this scenario is 14,632 ft^2, such that the area normalized O&M costs are \$0.13/ft^2 for the GSHP system and \$0.31/ft^2 for the packaged rooftop unit system. Other sources indicate that the O&M costs for a GSHP system are likely to range from \$0.06/ft^2 to \$0.11/ft^2, and that those for conventional systems can be three times as much. Assume that the O&M costs for the GSHP system are \$0.11/ft^2 and that the O&M costs for the baseline system are \$0.26/ft^2 (matching the ratio of O&M costs between the packaged rooftop unit system and the GSHP system from the Oregon study)