PNNL-23506

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The Cost-Effectiveness of Investments to Meet the Guiding Principles for High-Performance Sustainable Buildings on the PNNL Campus

August 2014

KA Cort
KS Judd

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

As part of its campus sustainability efforts, Pacific Northwest National Laboratory (PNNL) has invested in eight new and three existing buildings to ensure they meet the federal requirements for high-performance sustainable buildings. Executive Orders 13514 and 13423 require that all new construction and major renovations of federal buildings comply with the Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings (HPSB Guiding Principles) and that 15% of each agency's existing buildings meet the Guiding Principles by fiscal year 2015. These investments are expected to benefit PNNL by reducing the total life-cycle cost of facilities, improving energy efficiency and water conservation, and making buildings safer and healthier for their occupants.

This study examines the cost-effectiveness of the implementing measures that meet the criteria for the Guiding Principles in three different types of buildings on the PNNL campus: offices, scientific laboratories, and data centers. For office buildings, a direct comparison was made of two identical buildings with similar functions—one that meets the Guiding Principles and one that does not. For PNNL laboratories, it was not feasible to isolate differences in the equipment and functions in the laboratories, so the researchers examined the performance of one laboratory before and after measures were implemented to meet the Guiding Principles. Finally, for data centers the researchers examined the cost-effectiveness of consolidating five smaller computer rooms distributed across the campus into one data center housed in a building that meets the Guiding Principles.

In each of the three case studies examined the measures taken to achieve the Guiding Principles demonstrated a high return on the investments made. Simple paybacks for total investments in the three case study buildings ranged from just 2 to 5 years; savings-to-investment ratios all exceeded the desirable threshold of 1; and the net present values associated with these investments were all positive.

Acronyms and Abbreviations

BLCC	Building Life-Cycle Cost
BSF	Biological Science Facility
cfm	cubic foot(feet) per minute
CSF	Computational Science Facility
DOE	U.S. Department of Energy
DSOM	Decision Support for Operations and Maintenance
EB	existing building
EMSL	Environmental Molecular Sciences Laboratory
EO	Executive Order
ETB	Environmental Technology Building
EUI	energy use intensity
F&O	Facilities and Operations
FEMP	Federal Energy Management Program
FIMS	Facilities Information Management System
FY	fiscal year
gal	gallon(s)
Gb	gigabit(s)
GP	Guiding Principle
HPSB	High- Performance Sustainable Building
HVAC	heating, ventilation, and air conditioning
ISB	Information Sciences Building
kBtu	thousand British thermal units
kgal	thousand gallons
kWh	kilowatt-hours
LCC	life-cycle cost
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
LSB	Laboratory Support Building
MBtu	million British thermal units
NC	New Construction
NPV	net present value
NSB	National Security Building
O&M	operations and maintenance
OMB	Office of Management and Budget
PNNL	Pacific Northwest National Laboratory

PSF	Physical Sciences Facility
PUE	power usage effectiveness
PV	present value
RPL	Radiochemical Processing Laboratory
sec	second(s)
s.f.	square foot (feet)
SIR	savings-to-investment ratio
VAV	variable air volume
VFD	variable frequency drive
W	watt(s)
WUI	water use intensity

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1.0 Introduction

Executive Orders (EO) 13423 and 13514 require that all new construction and major renovations of federal buildings comply with the Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings (HPSB Guiding Principles) and that 15% of an agency's buildings meet the Guiding Principles by fiscal year 2015 (FY15). High Performance Sustainable Buildings (HPSBs) are those that employ integrated design principles, optimize energy performance, protect and conserve water resources, enhance indoor environmental quality, and reduce the environmental impact of materials.

Ideally, buildings meeting the Guiding Principles would exemplify how making cost-effective investments up front significantly reduces the building operating costs over the long run. However, the upfront capital and administrative investments associated with meeting the Guiding Principles and planning new building construction or major renovations often deter building owners because capital is difficult to acquire and administrative changes can be difficult to implement.

This study addresses the question of whether measures implemented to achieve the Guiding Principles have provided a return on the initial investment by analyzing the life-cycle costs (LCCs) and benefits for three different types of building spaces—offices, scientific laboratories, and data centers—on the Pacific Northwest National Laboratory's (PNNL's) campus in Richland, Washington. The study was commissioned by the U.S. Department of Energy's (DOE's) Sustainability Performance Office.

2.0 Building Characteristics

The PNNL campus is located at the northern boundary of the City of Richland in Washington State. Together, PNNL and DOE's Pacific Northwest Site Office have approximately 4,000 employees occupying more than 65 owned or leased buildings on the PNNL campus; 35 of these facilities are included in the DOE Facilities Information Management System (FIMS) and subject to the goal that 15% of existing buildings meet the criteria for HPSBs.

The buildings on the PNNL campus are primarily made up of the following types of space: laboratories (e.g., radiological, chemistry, biological, engineering, and instrumentation), offices, data centers, and warehouses. Any given laboratory facility typically houses multiple uses and types of space. For example, the William R. Wiley Environmental Molecular Sciences Laboratory (EMSL) is composed of a large data center, office space, and multiple types of laboratories. Because of the mixed uses and multiple functions within and among these buildings, it is very difficult to make direct performance comparisons related to energy and water usage.

2.1 Guiding Principles for High-Performance Sustainable Buildings

As noted above, EOs 13514 and 13423 require that new construction and major renovations of federal buildings comply with the HPSB Guiding Principles and that 15% of existing federal buildings must meet the Guiding Principles by FY15. Buildings that were third-party certified to meet the requirements of a multi-attribute green building standard or rating system (e.g., Leadership in Energy and Environmental

Design [LEED®]) prior to October 1, 2008, are also considered compliant with the Guiding Principles (IAWG 2008).

The DOE has interpreted the EOs and HPSB Guiding Principles to include buildings attaining third-party certification after October 2008, as well, but notes that these equivalences are contingent upon approval from the Office of Management and Budget and the Council on Environmental Quality. Specifically, DOE considers buildings meeting any of the following criteria as being in compliance with the Guiding Principles: LEED-New Construction (NC) Gold or LEED-Existing Building (EB) Silver certification or higher; Green Globes-NC rating of four or Green Globes-EB rating of three; or any building occupied for more than 1 year that achieves Living Status designation by the Living Building Challenge (DOE 2013).

The HPSB Guiding Principles for new construction and existing buildings focus on integrated management practices, energy and water performance, indoor environmental quality, and the environmental impact of materials. A building meeting the HPSB Guiding Principles must meet all of the criteria in each of these categories. The LEED rating system addresses six similar categories—sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation—but differs in that the user may choose the combination of criteria that will lead to the desired LEED rating.

As of FY13, 11 out of 35 buildings on the PNNL campus that are listed in the FIMS (31%) meet the Guiding Principles either through the federal HPSB requirement or through LEED certification. To help PNNL increase the number of buildings that meet the Guiding Principles, PNNL is moving toward a system where continuous building commissioning takes place on a routine basis using the Building Operations and Control Center to confirm that all building systems meet requirements as intended by building owners and as designed by building architects and engineers (PNNL 2013).

2.2 Building Selections for Comparison

To study the life-cycle costs and benefits of buildings meeting the Guiding Principles compared with other buildings on the PNNL campus, the physical and functional characteristics of the 35 buildings included in the FIMS were considered. For the purposes of this study, we focused on relatively larger buildings (e.g., 20,000 s.f. or more) that were primarily composed of scientific laboratories, office space, and data centers or some combination of these space types. Table 1 (at the end of Section 2.0) lists the buildings examined, ordered by their energy use intensity (EUI), defined as 1,000 British thermal units (kBtu) per square foot (ordered from highest intensity to lowest). As observed in Table 1, the function of the building influences its EUI. Buildings housing data centers (e.g., rooms with a large amount of computing power, server stacks, and redundant power systems) and certain laboratory functions have a much higher EUI than buildings whose primary function is providing office space.

The initial intent of the study was to compare buildings that comply with the Guiding Principles to those that do not when similar sets of buildings could be established by type and function, and normalized for occupancy and other factors. After reviewing the various functions and types of equipment in these buildings and data availability, it was determined that a building-to-building comparison was only feasible for two of the office buildings. To analyze the cost-effectiveness of investments in buildings housing laboratories, it was determined that the most accurate basis for comparison would be a before-and-after comparison for the same building. For data centers, it was determined that the most credible analysis of cost-effectiveness would be to assess the impact of a recent effort to consolidate several data centers previously housed in multiple smaller rooms in facilities into a single larger room housed in a facility designed to meet the Guiding Principles.

2.3 Measuring and Comparing Building Performance and Costs

The requirements for complying with the Guiding Principles extend beyond optimizing energy and water performance, to include enhancing indoor environmental quality and reducing the impacts of materials consumed. The scope of the cost-effectiveness analysis focused exclusively on the quantifiable energy- and water-related benefits and costs, where the benefits are energy and water cost reductions relative to the costs to implement and maintain these measures. Other economic benefits that may result from implementing Guiding Principle measures, including improved occupant health and productivity and reduced waste costs, were not considered because they are not easily measured and/or no data were available to support a building-level analysis.

When evaluating the life-cycle benefits and costs of a building, it is important to consider a time frame for the analysis that reflects the useful life of a given technology. For each measure considered, the lifetime of the equipment and its replacement and maintenance needs are considered over a 20-year period to align with facility planning horizons. For activities that affect overall building energy consumption, the lifetime of the savings is assumed to extend the length of the analysis period with consideration of corresponding maintenance and costs throughout the same period.

For all case studies examined, the energy and water savings are measured as the actual historical annual savings relative to the defined baseline. To sustain savings levels in the future, it is assumed that various buildings would need to undergo some form of building commissioning or retuning appropriate for the buildings. To calculate the savings in terms of dollars, the total annual savings is multiplied by the average cost per British thermal unit (Btu) based on actual historical costs, blending both electricity and natural gas costs per unit of consumption where relevant. The water rates are also based on historical rates as documented in recent PNNL building audits conducted in the Physical Sciences Facility (PSF) (Brown et al. 2013). Future energy rates are escalated based on DOE's Energy Information Administration (EIA) assumptions embedded in the Building Life-Cycle Cost (BLCC)[1] program, which is used to calculate the net present savings and the savings-to-investment ratio (SIR) of the energy- and water-conservation measures. Key assumptions for the analysis are summarized in the Appendix of this report.

When available from PNNL Facilities and Operations (F&O), the costs of various HPSB measures are based on actual costs of the measures. For cases where actual cost information is not available, costs are estimated based on a combination of sources including RS MEANS (RS MEANS 2002, 2014a, 2014b), Faithful & Gould (BC3 2011), and recent energy audit studies (e.g., Brown et al. 2013; Johnson et al. 2014; Ayers 2011). All costs and benefits are presented in 2014 dollars.

[1] Economic analysis tool developed by the National Institute of Standards and Technology for the U.S. Department of Energy Federal Energy Management Program (FEMP 2013).

Table 1. Buildings considered for comparison on the PNNL campus.

Building Number	Building Name	Predominant Function	Building Vintage	Meets Guiding Principles?	Square Footage	Occupancy	FY13 Water (gal/s.f.)	FY13 Energy (kBtu/s.f.)
3020	William R. Wiley EMSL	Bio/chem/instrument labs; data center/office	1997	No	234,566	472	43	487
CSF	Computational Sciences Facility	Data center; office	2009	Yes - LEED-NC Gold (2010)	74,000	122	18	398
331	Life Sciences Lab	Bio lab	1970	No	120,751	85	25	335
3430	Ultra Trace Building	Rad lab	2010	Yes - LEED-NC Silver	70,299	45	2	318
3420	Radiation Detection Building	Rad lab	2010	Yes - LEED-NC Silver (2010)	81,369	134	2	244
325	Radiochemical Processing Laboratory	Rad lab	1953	Yes – HPSB Guiding Principles EB (2013)	144,820	154	3	229
3410	Material Science and Technology Building	Chemistry lab	2010	Yes - LEED-NC Silver (2010)	79,878	72	44	211
ISB2	Information Sciences Building - 2	Office/data center	1992	No	60,080	267	12	192
BSF	Biological Sciences Facility	Bio lab	2009	Yes - LEED-NC Gold (2010)	71,000	120	19	125
Sigma 5	Sigma 5 Office/Lab Building	Office[a][b]	1981	No	47,900	170	NA	120
NSB	National Security Building	Office	1993	No	100,358	318	4	100
ETB	Environmental Technology Building	Office	1994	No	100,358	384	5	82
ISB1	Information Sciences Building - 1	Office/data center	1991	No	50,200	238	9	63
Sigma 1	Sigma 1 Office Building	Office[b]	1977	No	20,000	79	9	63
LSB	Laboratory Support Building	Office/data center	1996	No	83,921	358	9	61
Sigma 3	Sigma 3 Office Building	Office[a][b]	1977	No	20,090	93	7	48
Sigma 2	Sigma 2 Office Building	Office[b]	1977	Yes - LEED-EB Gold (2012)	20,100	86	31	43
Sigma 4	Sigma 4 Office Building	Office[a][b]	1978	Yes - LEED-EB Silver (2013)	20,530	63	9	39

(a) Offices have recently been retired (i.e., leases not extended).
(b) The water consumption for these buildings also includes outdoor water consumption for multiple other buildings.
EB = Existing Building; NA = not available; NC = New Construction.

3.0 Office Buildings

To compare the performance of office buildings at a high level, we examined the energy and water performance of seven buildings whose primary function was to provide office space, two of which meet the HPSB Guiding Principles. The EUI of these buildings was examined for the 10-year period from FY03 to FY13 (see Figure 1). Water use was also examined although the available metering data did not allow for direct comparison of water use intensities in several cases (as noted in Table 1). Office buildings that housed large data centers were excluded so that energy from heating, ventilation, and air conditioning (HVAC), lighting, and plug loads to support office space would not be skewed by the more energy-intensive data centers; however, the data reflected in Figure 1 are not normalized for computing or other equipment used in these buildings.

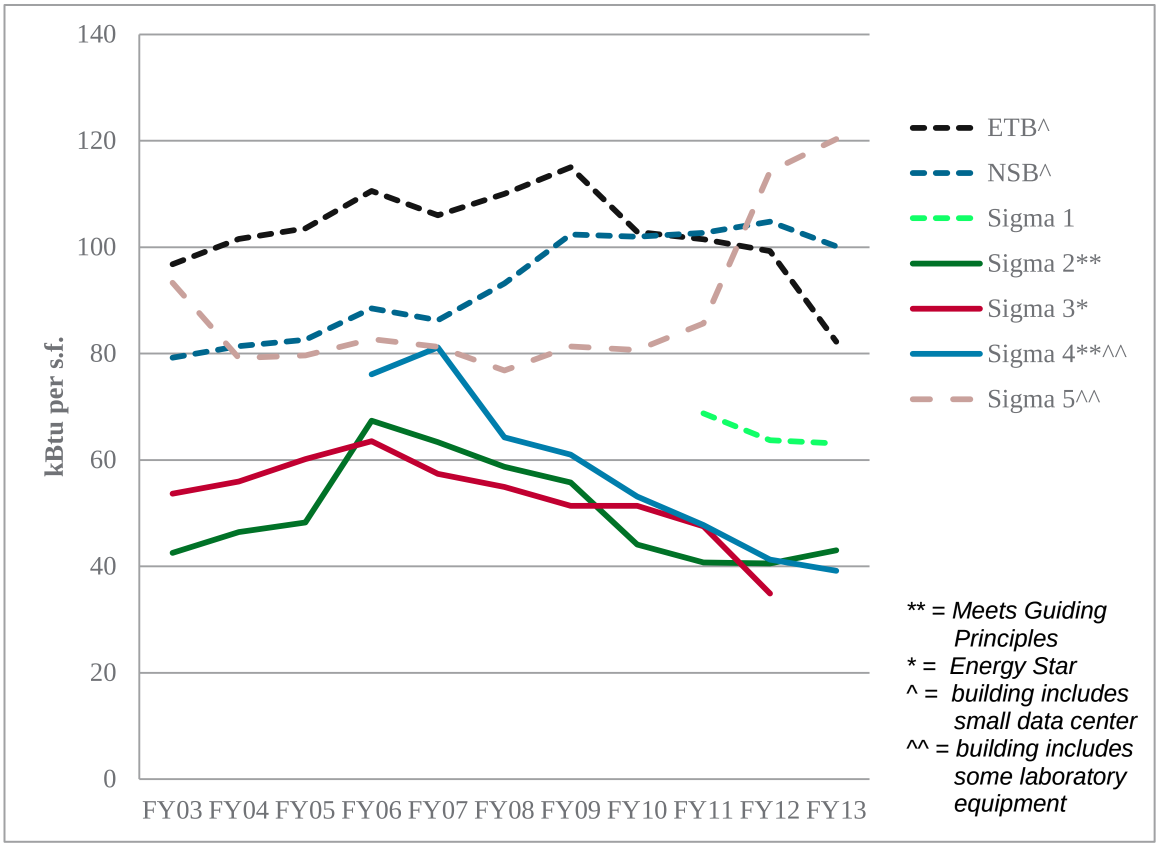

Figure 1. Office building energy use per square foot.

In 2012, the Sigma 2 office building became PNNL's first building to meet the Guiding Principles with LEED-EB Gold certification. As part of the original leasing agreement with PNNL, the Sigma 2 building had previously undergone several energy-efficient retrofits, including the addition of 4 inches of insulation to the exterior walls and upgrading the lighting system from T-12 to the more efficient T-8 fluorescent fixtures with electronic ballasts. These retrofits helped Sigma 2 achieve U.S. Environmental Protection Agency (EPA) ENERGY STAR facility recognition in 2002 (and again in 2005 and 2009). In addition to the energy-conservation measures, Sigma 2 has retrofitted four of the eight toilets and all of the urinals in the building to be high-efficiency water fixtures.

Sigma 4 met the Guiding Principles with LEED-EB Silver certification in 2013. Although Sigma 3 had not been demonstrated to comply with the HPSB Guiding Principles as PNNL ended its lease in 2012, Sigma 3 had implemented enough energy-conservation measures to achieve EPA ENERGY STAR certification in 2008. ENERGY STAR building certification requires a score of 75 or higher—the same as the energy-efficiency requirement for the Guiding Principles—so this building provides another useful point of reference when comparing the EUIs of PNNL office buildings.

In contrast to the energy- and water-conservation measures implemented in Sigma 2, 3, and 4, Sigma 1 and Sigma 5 have only been minimally retrofitted in terms of conservation measures. Likewise, the Environmental Technology Building (ETB) and National Security Building (NSB) have not met the Guiding Principles or achieved ENERGY STAR certification, and have not been retrofitted with any significant energy-conservation measures. As shown in Figure 1, the buildings that received significant energy-efficient retrofits (indicated with solid lines in the figure) have a noticeably lower EUI over time than the buildings that did not implement these same measures; however, variation in building activities and functions does not allow for a direct "apples-to-apples" comparison across all buildings in terms of energy use.

In addition to the energy-related features and systems of a building, energy performance is influenced by the type of building envelope construction and materials, the building size, configuration, orientation, occupancy, building activities, and weather. Although the weather is the same for each building on campus and one can control for occupancy levels, it is not possible to isolate the effects of these energy-saving measures across all office buildings because of the variations in building design, size, materials, and activities. Two of the office buildings (ETB and NSB) highlighted in Figure 1, for example, house small data centers and Sigma 5 houses some laboratory equipment, which could affect the energy intensity of the buildings. Sigma Buildings (see Figure 2) 1, 2, 3, and 4, however, share the same design, size, configuration, and primary activities so that variations in building energy and water use can primarily be attributed to the energy-efficient retrofits and features of these building, while controlling for variations in occupancy. Thus, to determine whether or not the energy- and water-efficiency investments in the Sigma buildings have paid off, we can compare the costs (e.g., retrofitting costs to meet Guiding Principles) and benefits (energy and water savings) between these buildings over the life cycle of the buildings.

Figure 2. Sigma 2 and 4 office buildings.

3.1 Case Study: Comparison of Sigma 1 and Sigma 2

Because of the varied time frame of leasing arrangements, the only direct comparison of energy and water consumption between a Sigma office building that does not meet the Guiding Principles and a similar Sigma building that was retrofitted to meet the Guiding Principles during the same time frame was a comparison between Sigma 2 (LEED-EB Gold) and Sigma 1 (limited efficiency and conservation measures). Table 2 describes and compares some of the energy- and water-related features of Sigma 2 and Sigma 1 buildings. Only 3 years of data for Sigma 1 and Sigma 2 were available for comparison over the same time period. During this time frame, the primary function of Sigma 1 and Sigma 2 was to provide office space to PNNL staff; however, 10% of the space in Sigma 1 was devoted to training rooms, which are large conference rooms equipped with a one large monitor and computer in each room. Although the training facility in Sigma 1 would increase the number of visitors and temporary occupants in the building, none of the training rooms is equipped with energy-intense equipment (e.g., individual computers for trainees).

Table 2. Sigma 2 and Sigma 1 energy and water-conservation features.

Sigma 2	Sigma 1
Envelope	
• Flat built-up roof with dark surface. • 4 inches of insulation added to exterior wall	• Flat, built-up roof with light (white) surface. • 2 inches of insulation added to exterior wall
Control Features (LEED-EB retrofits)	
• Network based, zone thermostats, and thermostat averaging • HVAC setbacks • Energy-saving lockout features (resistance heating controls, economizers, and staggered warm-up periods) • Automatic lighting features (offices, corridors, restrooms, conference rooms) • DSOM[(a)] features (view energy and water trending) • Daily verification of set-points by technician	• Lighting occupancy sensors installed in some of the conference rooms.
HVAC	
• 12 rooftop packaged heat pumps (6 of 12 units have been replaced during the past 10 years, but these have been end-of-life replacements. They were replaced with standard efficiency units that met minimum energy code standards)	• 12 rooftop packaged heat pumps (no information available on replacements)
Lighting	
• Converted from T-12, magnetic ballasted lamps to T-8, electronic ballasted lamps	• Converted from T-12, magnetic ballasted lamps to T-8, electronic ballasted lamps
Water Conservation	
• Water-efficient toilets and urinals; water-efficient faucets (with sensors) in bathrooms	• Water-efficient faucets (with sensors) in bathrooms

(a) Decision support operations and maintenance (DSOM) is software system that integrates information on plant operations, fuel management, and maintenance processes to help reduce operating and maintenance costs.

Figure 3 shows the average annual energy consumption for the two buildings. Despite the fact that Sigma 2 has 9% more full-time occupants (where each occupant would be associated with energy-consuming devices and office space), on average, the building consumes 36% less energy than Sigma 1 (see Figure 3). Based on an assessment of training activities (e.g., number of trainees and hours of activities) taking place within Sigma 1, it was determined that the temporary occupants in Sigma 1 would add an equivalent of 5 full-time occupants to the building. When normalizing for full-time occupancy, Sigma 2 consumes 40% less energy than Sigma 1 per occupant; however, because we are unable to accurately account for the effect the temporary occupants associated with training activities in either building,[1] for this analysis we use the more conservative whole building energy comparison to approximate the impact that energy-efficiency and energy-conserving measures have on Sigma 2.

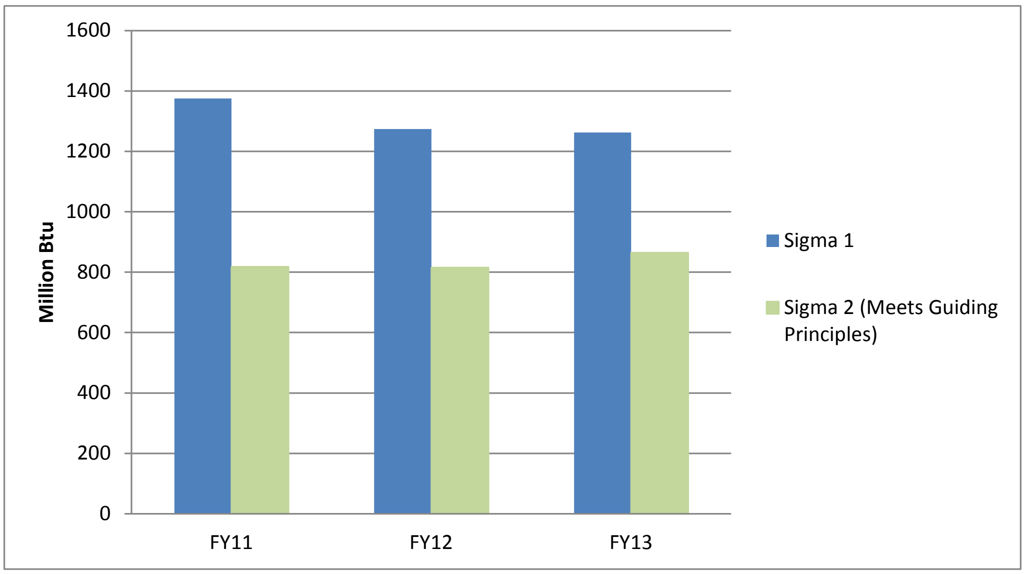

Figure 3. Comparison of annual building energy consumption.

As previously noted, because the training activities taking place in the Sigma 1 training spaces would not be associated with individual computing devices that would consume energy and produce heat, we would not expect these activities to necessarily skew energy consumption in the building. With regard to water consumption, however, a high number of building visitors would likely affect the amount of water consumed in the bathrooms. Sigma 1 is currently not equipped with water-efficient toilets or urinals and it consumes approximately 40−50% more water than Sigma office buildings that are equipped with water-efficient fixtures. To approximate and isolate the impact that the water-efficient features have on water consumption versus the higher throughput of training visitors, for this analysis we substitute the per occupant water usage from a Sigma building with equivalent bathroom fixtures (Sigma 3) to estimate and compare the amount of water usage associated with full-time occupants and bathroom fixtures. Results suggest that water consumption is reduced 33% by using the water-efficient toilets and urinals in the bathrooms.

[1] Although we can examine the number of temporary occupants in Sigma 1 training facilities throughout the year, we are not able to account for the temporary occupants in other conference rooms within Sigma 1 and Sigma 2. We also are not able to account for type of equipment some of the temporary occupants may bring with them and what influence this temporary occupation may have with regard to the timing (seasons) they occupy the buildings.

These savings are consistent from year to year over the time period examined. To calculate the savings in terms of dollars, the total annual savings is multiplied by the average cost per Btu based on actual historical costs. For Sigma 1 and Sigma 2 the average unit cost for energy is $19.5/MBtu. Demand charges are factored into the overall cost of energy. The actual effective marginal water and sewer rates are used in this analysis to calculate water and sewer savings (water is $0.9358/kgal, and $2.874/kgal for sewer). Assumptions related to energy and water rates and other cost parameters are described in the Appendix of this report.

3.2 Life-Cycle Cost-Effectiveness Analysis

A life-cycle approach is used to compare the cost and performance attributes of the Sigma 1 and Sigma 2 buildings; it takes into account the costs of acquiring and maintaining building energy and water-related systems in each building. Only the incremental costs of the improvements made to Sigma 2 to meet the Guiding Principles are considered. For example, both Sigma 1 and Sigma 2 added insulation to the exterior wall, but Sigma 2 added 2 additional inches; thus, only the additional cost of adding 2 more inches of insulation is considered because this is the cost of the improved insulation level in Sigma 2 compared to that in Sigma 1. Table 3 presents the assumptions related to the incremental investment costs, replacement costs, and ongoing operations and maintenance (O&M) costs related to the energy- and water-conservation measures. An examination of O&M records during the past year did not reveal any significant differences in O&M expenditures between these buildings. To keep the sensor and control systems in working order and properly tuned from year to year, it was assumed that approximately $2,000 additional dollars would need to be invested in Sigma 2 every 8 years to properly maintain control systems implemented to achieve the LEED-EB Gold certification.

Table 3. Incremental costs of measures to comply with Guiding Principles in Sigma 2 compared to Sigma 1.

Initial Installed Costs of Measures in Sigma 2	Incremental Cost over 20-Year Lifetime
• **Envelope upgrades:** Sigma 2 added 4 inches of insulation on exterior wall, while Sigma 1 only added 2 inches. Cost of additional 2 inches of insulation estimated at $.60/s.f.[a]	$2,560
• **Controls:** LEED-EB implementation (e.g., administration) costs and associated control upgrades (Sigma 2 actual costs)	$20,220
• **HVAC**: No difference in installed systems	$ --
• **Lighting**: No difference in installed systems	$ --
• **Toilet/urinal retrofits** (8 units at $550 per unit installed)[b]	$4,400
Incremental O&M Costs of Measures	
• No significant difference in O&M costs between Sigma 1 and Sigma 2	$ --
Replacement Costs and Recurring O&M Costs of Guiding Principle Measures (during 20-year life cycle)	
• Present value of future costs − assumes $2,000 replacement and nonrecurring O&M cost every 8 years for sensor and control replacements and maintenance retuning	$2,825

(a) Insulation costs from BC3 database (2014)
(b) Brown et al. (2014)
(c) Based on recommissioning estimate at $0.20/s.f. (Mills, et. al. 2009)

The BLCC[2] program was used to calculate the net present savings and the SIR[3] of the energy- and water-conservation measures. Table 4 presents the results of this life-cycle analysis, using Sigma 1 as the baseline for this analysis. Overall, there has been a substantial and relatively rapid return on the conservation measures implemented in Sigma 2 in terms of the overall SIR (4.35), the simple payback (4 years), and the net present value (NPV = $96,340) of the investments. Typically, any investment with an SIR of 1 or higher would be considered sound over the time horizon considered.

Table 4. Office building life-cycle cost analysis results.

	PV of LCC Energy Costs	PV of LCC Water Costs	Incremental Installed Cost	PV of LCC O&M Costs			
Sigma 2 (Meets Guiding Principles)	$217,384	$6,456	-$27,180	-$2,825			
Sigma 1 (Baseline)	$339,655	$10,530	--	$0			
					Simple Payback (years)	SIR	Net Present Value of Savings
Net Savings (Costs) from Measures to Meet Guiding Principles	$122,271	$4,074	-$27,180	-$2,825	**4**	**4.35**	**$96,340**

4.0 Laboratories

Figure 4 displays the EUIs for selected laboratory buildings on the PNNL campus for the past 5 years. Several newer laboratories built in recent years have been designed and built to LEED-NC Gold and Silver standards including the Computational Science Facility (CSF), the Biological Science Facility (BSF), and the PSF laboratories (Buildings 3410, 3420, and 3430) (see Figure 4). In addition, the Radiochemical Laboratory (RPL) has been retrofitted with several water- and energy-conservation measures and the building meets the HPSB Guiding Principles.

[2] Economic analysis tool developed by the National Institute of Standards and Technology for the U.S. Department of Energy Federal Energy Management Program (FEMP 2013).
[3] The SIR is defined as the total present value (PV) energy savings over the lifetime of the improvement divided by the upfront costs of the investment plus the PV of future maintenance costs.

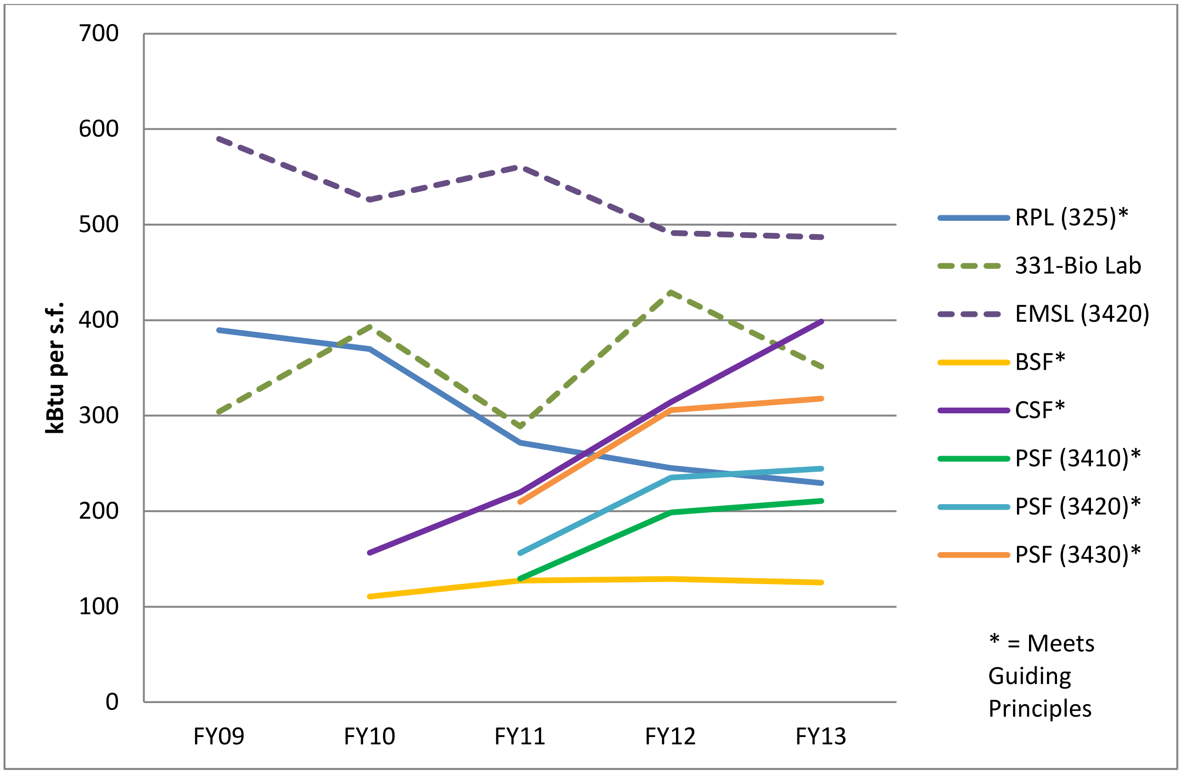

Figure 4. Laboratory building energy use intensities on the PNNL campus.

Overall, as shown in Figure 4, PNNL laboratories that meet the Guiding Principles for either new construction or retrofits to existing buildings appear to have lower EUIs on average. However, it is difficult to attribute energy use solely to the energy systems and conservation measures because the energy use of certain laboratory equipment may vary significantly based on its function and manner of use. In addition, some of the newer buildings have been ramping up operations and occupancy during the first 2−3 years of operation; thus, it is difficult to compare performance given these changes in operation over time.

4.1 Case Study: RPL Before-and-After Retrofits

While the original intent of this study was to compare laboratory buildings that meet the Guiding Principles with those that do not, it was determined that the varied equipment and functions of the candidate laboratories would not allow for a credible side-by-side comparison of buildings to isolate the impact of measures taken to meet the Guiding Principles. Therefore, to assess the impact and cost-effectiveness of these measures, we examined a before-and-after case for one laboratory, the RPL. The usage is normalized for occupancy, and the energy use over multiple years (both before and after meeting the Guiding Principles) is averaged to diminish any effects from weather variation from year to year. As shown in Figure 4, the EUI of RPL dropped significantly between FY10 and FY12. The EUI reductions stem from an overall 25% drop in energy use, normalized for occupancy, during this time frame.

The RPL is a 145,000 s.f. radiochemical processing laboratory that was constructed in 1953 (see Figure 5). To meet one of the most difficult requirements of the Guiding Principles (i.e., 20% reduction in energy use compared to the 2003 baseline year), significant building improvements were necessary.

Using the HPSB Guiding Principles, the facility was thoroughly audited and several repairs and retrofits were instituted to dramatically reduce energy and water usage (Ayers 2011; Pope 2013). The retrofits included the following:

- revamped the heat-recovery system; identified and fixed several leaks
- replaced existing chillers with high-efficiency chillers (two 300-ton chillers air-cooled variable frequency drive [VFD] screw chillers)
- added cooling coils dedicated to the chilled water system and upgraded 11 variable air volume (VAV) units
- replaced metal halide outdoor lighting with light-emitting diode (LED) lighting
- installed meters to measure electricity, natural gas, and water usage
- installed occupancy-based lighting controls
- installed high-efficiency plumbing fixtures.

Figure 5. Radiochemical Processing Laboratory (Building 325)

Table 5 lists the measures that were implemented at RPL to improve the energy and water performance of the building.

Table 5. List of measures implemented in RPL to achieve the Guiding Principles.

Control Features
• Installation of sub-meters
• Installed occupancy-based lighting controls
HVAC
• Revamped heat-recovery system (repaired system by finding and fixing leaks)
• Replaced chillers with high-efficiency chillers
• Added dedicated cooling coils to the chilled water system
Lighting
• Installed LED lighting in parking lot
Water Conservation
• Reduced steam usage from boiler, which reduced boiler makeup water needs
• Installed high-efficiency plumbing fixtures, including low-flow urinals and sensor faucets

Comparing the energy use of RPL just prior to the completion of these energy-saving repairs and retrofits suggests that the combination of all retrofits resulted in a 25% reduction in energy use when controlling for occupancy. An even more dramatic reduction was experienced in water usage, where use per occupant was reduced by more than 70% (see Figure 6). The repairs and modifications to the heating and cooling systems vastly reduced the amount of bleed-off water for the steam system, and RPL now uses very little potable water to improve building energy efficiency. In addition, high-efficiency urinals were installed in men's restrooms and high-efficiency faucets equipped with motion sensors were installed at restroom sinks. RPL does not have any outdoor landscaping or water use.

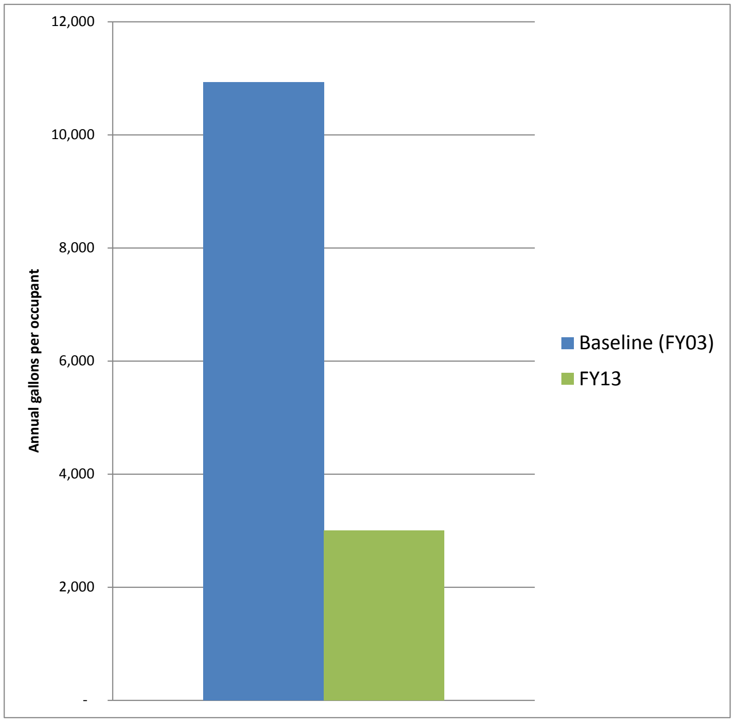

Figure 6. Comparison of annual "before and after" water usage at RPL.

4.2 Life-Cycle Cost-Effective Analysis

Table 6 presents estimates of the investments in measures to meet Guiding Principles for the RPL building. All costs are presented in 2014 dollars. The O&M costs, as well as future commissioning and control replacement costs, are also included as part of the cost estimates. Based on recent experience and input from facilities personnel, routine O&M costs are not expected to change for HVAC maintenance. However, the LED outdoor lighting retrofits are assumed to reduce O&M expenses over time, because LEDs would require fewer replacements than the standard metal halide lighting in place before the retrofit; thus, the present value of these expenses is presented as a negative number.[4] To maintain the savings over time, it is assumed that major recommissioning activities would need to take place at least once during the 20-year life cycle examined as part of this analysis. Commissioning activities are estimated to cost $.20/s.f. (building is 145,000 s.f.) (Mills et al 2009).

[4] See "Lighting Costs" in Appendix of this report for further explanation with regard to how O&M lighting costs are determined throughout the study period.

Table 6. RPL incremental costs of measures implemented to achieve Guiding Principles.

Initial Installed Costs	Total Cost of Retrofits
• **Controls:** Occupancy-control upgrade and commissioning (RPL actual costs)	$21,779
• **HVAC[a]:**	
– Cost to replace two 300-ton air-cooled VFD screw chillers	$880,000
– Upgrade of 11 VAV units	$154,000
– Cost to repair heat-recovery system	$5,000
– Additional dedicated cooling coils	$30,000
• **Lighting:** Retrofit 4 parking lot lights with LED fixtures and sensors	$7,800
• **High-efficiency plumbing upgrade:** replacement of 4 units estimated at $550 per unit installed[b]	$2,200
O&M Costs	
• O&M discounted net savings from LED replacement (fewer replacements needed over 20-year period) • No significant difference in O&M expected with other (e.g., HVAC) energy-saving measures	($3,868)
Replacement Costs and Nonrecurring O&M Costs (during 20-year life cycle)	
• Discounted commissioning costs assuming that savings are maintained over 20-year life of equipment with one major retro-commissioning effort after 10 years, cost at $.20/s.f..[c]	$20,950

(a) HVAC costs based on RS Means Mechanical Costs and adjusted based on PNNL facility management experience with RPL repairs and equipment replacement.
(b) Brown et al. (2013)
(c) Mills et al. (2009)

An LCC approach is used to evaluate the cost-effectiveness of the energy- and water-conserving measures at RPL, comparing the cost and performance attributes of RPL before and after the building measures were implemented. As with office building comparisons, the BLCC is used to calculate the NPV of savings and costs over time. Table 7 presents the results of this life-cycle analysis, using BLCC default assumptions for discounting and energy/water escalation rates.

Because it was not possible to delineate the energy and water savings attributable to each measure, the analysis examines total savings and compares this to the total costs of implementing measures, including the total cost of chiller replacement and repairs. The results of this comparison are presented under "Scenario A" in Table 7. The Scenario A baseline characterization assumes that the RPL HVAC will continue to function without replacement. This assumption, however, is not practical considering that the chiller in RPL was prematurely failing and would have needed replacement, regardless of whether or not the Guiding Principles were applied. The more reasonable baseline characterization would have involved a replacement of the chiller, but it is likely that this chiller would have been replaced with a standard efficiency chiller, because the approach to meeting the Guiding Principles is credited with guiding the process to install higher efficiency chillers than would have normally been installed as well as implementing other energy- and water-efficiency measures, retrofits, and repairs (Pope 2013).

To further examine the cost-effectiveness of these measures, a second baseline scenario is presented (Scenario B in Table 7). Scenario B credits the efforts to meet the Guiding Principle as influencing the decision to replace the chiller system with a higher efficiency system as well as institute more comprehensive HVAC system retrofits (e.g., fix reheat system, add coils and new VAV units), upgrade parking lighting to LEDs, upgrade the plumbing to water-efficient fixtures, and institute optimal control strategies. In this scenario, it is presumed that for the baseline, chiller replacement would have occurred but would have involved slightly lower efficiency units. All other retrofitting measures (e.g., occupancy controls, lighting retrofits, etc.) would not have occurred. Under baseline Scenario B, a standard chiller replacement is assumed to reduce energy consumption by 6% throughout the 20-year evaluation period and would have cost approximately 10% less to purchase and install than the higher efficiency units. Table 7 presents the results of this analysis for Scenarios A and B.

Table 7. Results of the life-cycle cost analysis of retrofits to achieve the Guiding Principles in a laboratory.

		PV of LCC Energy Costs	PV of LCC Water Costs	PV Installed Cost	PV of LCC O&M Costs			
SCENARIO A	All Measures to Meet Guiding Principles	$9,824,420	$26,189	$1,100,779	$20,950			
SCENARIO A	Baseline: No Energy-Related Measures	$13,247,525	$92,144	$0	$3,868			
SCENARIO A	SCENARIO A					Simple Payback (years)	SIR	Net Present Value of Savings
SCENARIO A	Net Savings (Costs) of Measures to Meet Guiding Principles	$3,423,105	$65,955	-$1,100,779	-$17,082	**5**	**3.11**	**$2,371,199**
SCENARIO B	All Measures to Meet Guiding Principles	$9,824,420	$26,189	$1,100,779	$20,950			
SCENARIO B	Baseline: No Energy-Related Measures	$12,165,135	$90,628	$802,560	$3,868			
SCENARIO B	SCENARIO B					Simple Payback (years)	SIR	Net Present Value of Savings
SCENARIO B	Net Savings (Costs) of Measures to Meet Guiding Principles	$2,340,715	$64,439	-$298,219	-$17,082	**2**	**7.55**	**$2,089,853**

Although the measures implemented to meet the Guiding Principles in RPL required a substantial upfront cost, the investments appear to have yielded a very high return in terms of the life cycle of the building, regardless of which baseline scenario is assumed. Scenario B demonstrates that it is particularly beneficial to consider measures to meet the Guiding Principles when a large investment in HVAC replacement is required or under consideration. The incremental cost to upgrade to a more efficient unit, as well as simultaneously consider and implement other efficiency measures yields a high return on the investment, with an SIR over 7, a 2-year simple payback, and an NPV of savings in excess of $2 million.

5.0 Data Centers

Data centers provide mission-critical computing functions essential to PNNL's daily operation. These data centers consume large amounts of energy to run and maintain their computer systems, servers, and associated high-performance components. To protect these systems and their vital functions, data centers also use energy-intensive HVAC systems, fire-suppression systems, redundant/backup power supplies, redundant internet connections, and high-security systems. Although data centers are inherently more energy-intensive than standard office space, the energy expended by the supporting facilities (e.g., HVAC systems) can be minimized when facilities are properly designed to meet the needs of data centers. A portion of PNNL's recently constructed CSF was designed to efficiently meet the energy needs of its data centers.

The CSF was constructed to meet the Guiding Principles as a LEED-NC Gold building and is cooled with an efficient aquifer heat exchange HVAC system. The closed-loop system circulates through rear door heat exchangers in the data center, pumping heat away from the chilled water compressors that feed the computer room air conditioners. As a result of the more tailored high-efficiency design and systems, the power usage effectiveness (PUE) ratio[5] for the CSF data center is 1.2, which is significantly lower than the PUE of similar data centers on the PNNL campus (see Figure 7). As part of DOE's sustainability efforts, PNNL has a goal to reduce the PUE of all data centers on the campus to 1.4 by FY15. The CSF is currently the only one of the three largest data centers to exceed this PUE goal (PNNL 2013).

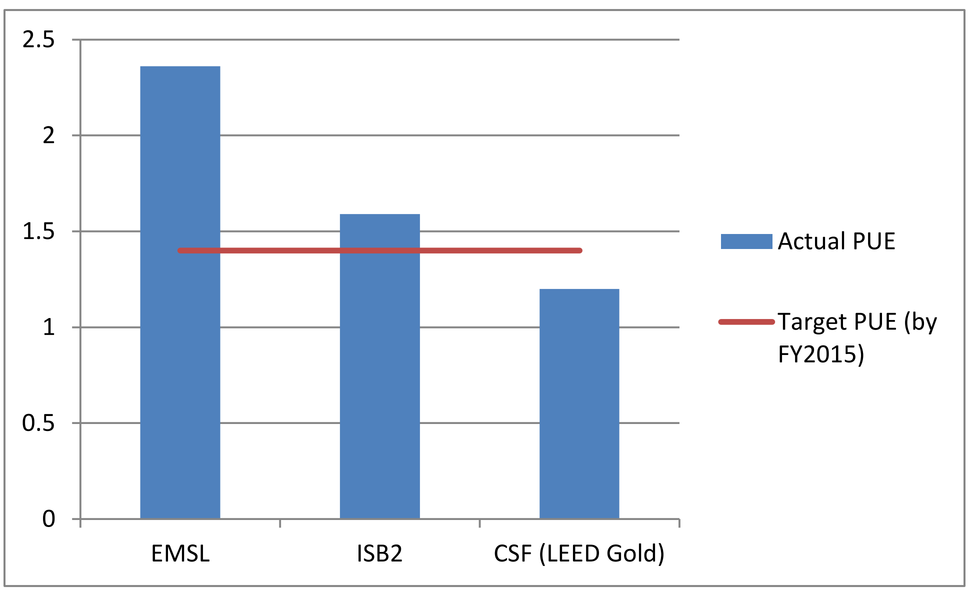

Figure 7. Comparison of power usage effectiveness between data centers.

[5] PUE = total facility energy/IT equipment energy.

5.1 Case Study: LEED Gold Data Center

Although the PUE comparison of the LEED Gold CSF, EMSL, and Information Sciences Building 2 (ISB2) data centers on the PNNL campus would suggest that CSF is the more energy-efficient data center, it is difficult to directly compare the overall benefits and costs of the energy performance of these three data centers without more specific metering and cost data. An alternative comparison, however, was available based on data collected before and after PNNL undertook the task of consolidating five smaller computer rooms (from PSF, ISB1, LSB [Laboratory Support Building], and ETB) into the larger more efficient CSF data center in 2012. The goal of the move was to free up space, reduce the number of data centers by 25%, and save energy by vacating energy-inefficient space. To isolate and examine the effects that measures to meet the Guiding Principles in CSF had on data center energy performance, energy-use data were examined from the five smaller computer rooms (Figure 8) before and after the move and compared to the newly constructed CSF building (Figure 9), which meters the energy use of the data center.

Figure 8. Data center cabinets and room before and after the move to the CSF.

Figure 9. The Computational Science Facility

The data center consolidation effort involved moving equipment from a number of locations to the more energy-efficient CSF building. In FY13, approximately 61% (as measured by square footage) of the operations housed in the decentralized computer rooms were consolidated and moved to the CSF and the vacated space was emptied and re-purposed for other uses.

The energy-saving features of the CSF design, which were not present in the smaller computer rooms, included the following:

- ground source cooling system
- water-cooled rear door heat exchangers for computer rack cooling
- environmental instrumentation allowing for higher operating temperature

- energy-efficient uninterruptible power supplies and transformers
- cooling system placed closer to the equipment, reducing cost and improving efficiency.

A follow-up walkthrough audit was performed to ensure that all systems were functioning as designed.

The five computer rooms added up to 2,857 s.f. and contained 67 computer racks. When the move was completed only 27 computer racks and 432 s.f. were needed, representing a 60% reduction in computer racks and an 85% reduction in floor space because a larger room supports cabinets in a more space-efficient manner. Despite an 85% reduction in space used for the data center, the EUI in the new facility only increased by 40%. Overall energy costs to support the data centers before the move was estimated to be $208,488 annually. After the consolidation, the energy costs were reduced to $44,465, resulting in annual savings of $165,023.[6]

5.2 Cost-Effective Analysis

Although there is a cost premium to build to the LEED-NC Gold standard relative to conventional construction, the more efficient use of space made the total of the resulting 432 s.f. of space a cost-effective choice when compared to replacement of 2,857 s.f. of space (see Table 8). The annual space costs for the original five rooms was $142,900; they are now collaboration areas, offices, and meeting rooms.

Table 8. LEED Gold data center construction costs and square footage.

	Standard Data Center	LEED Gold Data Center
• Cost per square foot[(a)]	$305	$336
• Data center square footage to support needs prior to consolidation	2857	
• Consolidated data center square footage in LEED Gold building		432
Building construction cost to meet data service demand needs	$871,385	$145,152

(a) Cost per square foot estimates for different building types are based on RS MEANS (2014b and 2011).

Table 9 presents the incremental costs of constructing a higher efficiency data center (at 432 s.f.) and consolidating the five existing data centers into one center on campus. Due to the reduction in square footage, the overall O&M costs are reduced after the consolidation. Presumably, other maintenance benefits would be derived from some of the higher efficiency systems, such as the higher efficiency lighting systems in the CSF; however, these actual costs could not be quantified. To ensure that savings are maintained, future retuning and commissioning efforts are factored into the ongoing costs of the CSF data center.

[6] Based on PNNL F&O memo titled, "Energy Savings and Usability Improvements through Data Center Consolidation." E-mail correspondence from Ralph Wescott, May 19, 2014.

Table 9. Cost of the consolidating five smaller data centers into a larger data center in a facility that meets the Guiding Principles.

Initial Installed Costs	Total Incremental Costs (Savings) of Retrofits
• **Building Cost** (for 432 s.f. data center)	$145,152
• **Consolidation Cost (facility move)** (actual cost)	$300,000
O&M Savings	
• Present value of O&M savings from having less space to maintain in consolidated data center • Higher efficiency lighting would also result in fewer bulb replacements (not quantified)	($17,854)
O&M Costs	
• Assume annual retuning to maintain higher level of efficiency in building meeting Guiding Principles. Portion attributable to 432 s.f. data center is approximately $100/year.	$1,488

Other non-energy benefits identified during the consolidation process include the following:

- increased security due to proximity card access, surveillance, better fire-protection and smoke-detection equipment in the CSF data center
- water cooling direct to the cabinet when energy density warrants
- detailed sensors monitoring energy use, temperature, and water flow to help proactively manage hot spots and PUE
- research staff are now able to focus on their applications and experiments instead of trying to manage a data center
- fewer maintenance issues to be dealt with by data center such that users can focus more time on experiments and less time on fixing problems
- faster networking that is professionally managed. Most of the servers that moved now reside in a 10-Gb/sec rather than a 1-Gb/sec environment. The network switches are better managed and monitored by the PNNL campus network team.
- best practices when it comes to outfitting a standard computer cabinet. There are 27 standards PNNL adheres to in order to increase manageability and minimize human-induced interruptions.

Table 10 provides a summary of the LCC analysis results. Considering that the total budgeted amount for the administration and implementation of the data center consolidation was $300,000, it appears that the decision to consolidate was well-justified in terms of return on investment, because the NPV of the consolidation is nearly $2 million. Removing rooms with poor PUE and increasing the footprint of our higher efficiency building to accommodate data center needs reduced energy use and helps PNNL trend toward achieving the PUE of 1.4 goal, as specified in EO 13514. Even when factoring in the incremental cost to construct a building to this higher level of efficiency, the SIR on the investment is 5.43 and simple payback is 3 years.

Table 10. Life-cycle cost analysis results.

	PV of LCC Energy Costs	Installed Cost	PV of LCC O&M Costs			
Consolidated HPSB Data Center	$650,513	$455,152	$1,488			
Baseline: Multiple Data Centers	$3,050,133	$0	$17,854			
				Simple Payback (years)	SIR	Net Present Value of Savings
Net Savings (Costs) from Consolidation and Move to CSF	$2,399,620	-$445,152	$16,366	**3**	**5.43**	**$1,970,834**

6.0 Conclusions

This study used three measures to examine the cost-effectiveness of implementing sustainable design and operations measures to meet HPSB Guiding Principles: simple payback, SIR, and NPV. Although the criteria used to determine whether or not an investment is cost-effective can vary, any building-related investment that has a simple payback period of 5 years or less is typically considered a cost-effective measure when applied to facilities and buildings where these measures last for many years. Typically an SIR[7] more than 1 indicates that the present value of the stream of benefits is greater than the present value of the LCCs for the project. A positive NPV indicates the PV of life-cycle benefits exceed the PV of LCCs of all of the measures.

In each of the three case studies examined for office buildings, laboratory buildings, and data centers, the investments made to achieve the Guiding Principles demonstrated a high return. Table 11 summarizes the results of the three case studies. Although the level of the initial investments for the three cases ranged from $27,000 to $1.1 million, in all three cases the simple payback ranged from 2 to 5 years. The SIR was more than 3 for all building types and the NPV was positive, ranging from $96,340 to over $2 million. The study also suggests that is worth the effort to consider and implement more comprehensive energy- and water-efficiency improvements when major upgrades (e.g., HVAC replacements, envelope modifications or any new construction) are being considered by facilities management.

Table 11. Summary of cost-effectiveness of investments in three facilities that meet the Guiding Principles.

Case Study	Simple Payback (year)	Savings-to-Investment Ratio	Net Present Value ($)
Office Building: Sigma 2	4	4.65	$96,340
Laboratory: RPL (Scenario A)	5	3.11	$2,371,199
Laboratory: RPL (Scenario B)	2	7.55	$2,089,853
Data Center: CSF	3	5.43	$1,970,834

[7] The SIR is calculated by dividing the total savings over the project's expected useful life by the cost of the project. This metric incorporates the expected life of the measure and accounts for the benefits throughout, but not past, the expected useful life of the measure.

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Appendix A

Key Assumptions

Appendix A

Key Assumptions

Topic	Assumption
Energy Cost	Actual blended average historical costs per million British thermal units used for RPL and Sigma 1 and 2. Assumed $.05/kWh for data center analysis.
Water Costs	$0.94/kgal (Brown, et. al. 2013)
Wastewater costs	$2.87/kgal (Brown, et. al. 2013)
Discount Rates	BLCC uses Office of Management and Budget (OMB) discount rates for cost-effectiveness, and related analyses are based on Treasury notes and bonds of varying maturities.
Study period	A 20-year study period is used as the time horizon for the building analysis.
Equipment Life	The equipment life for chillers, boilers, and variable air volume (VAV) systems is assumed to be 20 years. Lighting varies by technology (see Lighting Costs). All envelope and plumbing retrofits (e.g., insulation and toilets) are assumed to have a lifetime that exceeds the study period.
Lighting Costs	For RPL parking light retrofits, it is assumed that 400-W metal halide lamps using old magnetic ballasts are replaced with light-emitting diode (LED) lights requiring a 200-W draw on power. Because LED lamps are integral to the fixture, the retrofit cost is relatively more substantial, requiring an electrician at $81/hour. The LED fixture has a life of about 80,000 hours. RPL lights are installed with light sensors and it is assumed that they operate 10 hours per day. It was assumed that subsequent lamp replacement would take 1 hour. Labor rates from RSMeans Mechanical Cost Data 2014 are used. The default used is the electricians' hourly rate with overhead and profit.
Square Footage Construction Costs	RS Means (2011; 2014b)
Commissioning Costs	Based on Mills E. (2009) "A Golden Opportunity for Reducing Energy Costs and Greenhouse-Gas Emissions." http://cx.lbl.gov/cost-benefit.html
SIR	The savings-to-investment ratio (SIR) is the ratio of operational savings to additional investment costs, calculated for the energy-saving alternative relative to a base case.
Escalation Rates	Energy rates are escalated based on energy price escalation rates projected by the U.S. Department of Energy's (DOE's) Energy Information Administration (EIA). A DOE/ National Institute of Standards and Technology computer program, Energy Escalation Rate Calculator (EERC), calculates an average annual escalation rate based on the EIA projections and weighted by the proportion of energy savings coming from each of the fuels used in the project.
Chiller Costs	From RS Means Mechanical (2014), the cost of chiller replacement is based on installed cost air-cooled variable frequency drive screw chillers at 300 tons each. Air handlers are based on 10,350 cfm air handler with 11 VAV units (estimated at 1000 cfm each). Additional coils are also based on RSMeans Mechanical (2014a). These costs are adjusted based on PNNL facility management experience with RPL repairs and equipment replacement.

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