Quantifying the benefits of a building retrofit using an integrated system approach: A case study

Cynthia Regnier, Kaiyu Sun, Tianzhen Hong*, Mary Ann Piette

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

*Corresponding Author. Email: thong@lbl.gov, Phone: (510) 486-7082, Fax: (510) 486-4089

Abstract

Building retrofits provide a large opportunity to significantly reduce energy consumption in the buildings sector. Traditional building retrofits focus on equipment upgrades, often at the end of equipment life or failure, and result in replacement with marginally improved similar technology and limited energy savings. The Integrated System (IS) retrofit approach enables much greater energy savings by leveraging interactive effects between end use systems, enabling downsized or lower energy technologies. This paper presents a case study in Hawaii quantifying the benefits of an IS retrofit approach compared to two traditional retrofit approaches: a Standard Practice of upgrading equipment to meet minimum code requirements, and an Improved Practice of upgrading equipment to a higher efficiency. The IS approach showed an energy savings of 84% over existing building energy use, much higher than the traditional approaches of 13% and 33%. The IS retrofit also demonstrated the greatest energy cost savings potential. While the degree of savings realized from the IS approach will vary by building and climate, these findings indicate that savings on the order of 50% and greater are not possible without an IS approach. It is therefore recommended that the IS approach be universally adopted to achieve deep energy savings.

Keywords: Building retrofit; integrated system; energy savings; energy conservation measures; building simulation; integrated design

1. Introduction

In the U.S. buildings account for 38% of all CO_2 emissions [1] as well as 73% of total electricity consumption [2]. Commercial buildings built in 2008 or later represent about 6% of the total stock and 7% of the total floor area of the commercial buildings built before 2012 [3], residential buildings built in 2000 or later take up only 14% of the total housing units built before 2009 [4], which means that more than 90% of the commercial and residential buildings in the U.S. are existing buildings. Approximately 61% of all construction projects are retrofit projects [5]. These facts draw attention to the critical impact existing buildings have on energy consumption and greenhouse gas (GHG) emissions.

A building energy retrofit is the process of modifying aspects of the building (after its initial construction and occupation) with the goal of improving its energy performance. According to Lawrence Berkeley National Laboratory's research using its NAESCO (National Association of Energy Service Companies) Database, retrofits by Energy Service Companies (ESCOs) have typically focused on electricity savings (accounting for over 80% of total energy savings) and produced reductions on the order of 15 to 30% percent of a building's electricity consumption [6]. Building retrofits can also offer significant opportunities for reducing global greenhouse gas emissions [7–9]. In terms of non-energy benefits, building retrofits can also reduce energy costs [10], improve indoor environmental quality such as by improving thermal comfort, indoor air quality, protection against external noise, and increase staff productivity and reduce maintenance cost [10–16]. Therefore, the retrofit of existing buildings can make a significant contribution to reduce energy consumption and GHG emissions while improving the performance of a building in other respects.

The simplest and most common retrofit approach is to upgrade existing equipment, where the equipment's efficiency improvements are the main contribution towards energy savings. Often these retrofits are implemented incrementally, applied one at a time over the course of several years, often coinciding with the end-of-life replacement of existing equipment, or with tenant improvements. This kind of traditional retrofit focuses on single pieces of equipment, such as chillers, or end-use systems such as lighting, with little emphasis on overall building performance, system optimization, controls integration or interactions among building systems [17]. The various systems in the building are generally treated as isolated individual systems and tend to be targeted for simple equipment replacement or lighting system upgrade [18]. Contractors will often focus on those end-uses in which they are most experienced [17] and consequently are less inclined to look for deeper Integrated System (IS) strategies that might involve other trades. Between 1990 and 1997, 53% and 25% of all retrofit projects were lighting-only retrofits for the private sector and public/institutional sectors, respectively [19]. The percentage for the private sector was also significant at 33% for lighting retrofits only from 2005 to 2008 [20]. Even when multiple energy conservation measures (ECMs) are considered across different end use systems, many large customers prefer a staged approach, such as when ECMs are implemented over time in multiple phases by ESCOs. This approach fits the culture of many owners and building managers who prefer a 'tried and true' approach to building retrofits and upgrades, by allowing the customer to assess performance on an initial project, which often involves a lighting retrofit, and then, if successful, the more complex or capital intensive measures in a second or third stage would be approved [6,21,22]. In these cases, opportunities to capture additional savings through designs that target multiple end-uses and strategically leverage interactive effects are lost.

To estimate the potential additional savings of an IS approach, it is important to quantify the interactive effects among various building systems. Markedly, the energy savings from multiple types of ECMs often differ from the sum of the impact of the individual ECMs. The effectiveness of multiple ECMs depends upon their interactive effects, which, if neglected, may lead to significant double-counting and overestimation of the overall reduction potential [9,23]. To address the problem simply, an interaction factor can be defined to indicate the extent to which the efficacy of an ECM is reduced [8,14]. However, the estimation of the interaction factor between any two building system options is complex. These interactions can be dealt with by carrying out detailed, systems-based modeling approaches, as there will be non-linearity in the way in which the system interacts with the building arising from factors such as the timing of service demands, building geometry, solar orientation and layout of the building. A more straightforward and reliable method is to use whole-building energy simulation, which is adopted in this study. Whole-building simulation, using programs like EnergyPlus, calculates the dynamics of building systems in detail, including their interactions.

At the same time, there are a number of inherent barriers to conducting building energy retrofits, such as a lack of awareness of energy efficient options, financial challenges [24,25], insufficient information [26], various uncertainties [27], complexity of decision making process, and interruptions to operations [28]. However, the need for greater energy efficiency is urgent. The Stern review proposes a reduction of greenhouse gas (GHG) emissions by approximately 76% by 2050 to stabilize the climate [29,30]. The long-term goal of the U.S. Department of Energy's Building Technologies Office is to reduce energy use by 50%, compared to a 2010 baseline [31]. With typical retrofits having far from sufficient energy savings to meet these targets, IS retrofits are needed. IS may be part of the solution to achieving the aggressive energy savings and GHG reduction goals, while supporting the delivery of other non-energy benefits such as thermal comfort.

Integrated design is an established process for the delivery of a building design, which requires all relevant stakeholders to be involved throughout the design process. Integrated Systems are a design feature that may result from such a process. Integrated systems are building systems that are interdependent on one another in order to achieve whole building goals, and may include strategies that enable technologies otherwise unviable without the support of related systems to reduce loads or enable other favorable conditions. For example, a lighting and shading strategy can be integrated with a radiant cooling HVAC system when the energy efficient lighting system and the shades reduce internal heat gains, including direct solar gain, to the point where cooling loads are decreased enough to enable the radiant cooling system as a viable strategy to condition the space. Radiant cooling systems have inherently lower cooling capacities and require this integrated approach to reduce cooling loads before they are considered viable to meet the cooling loads of the space. As they move beyond straightforward lighting or chiller replacements, IS retrofits are a package of integrated building energy efficiency measures that optimize energy savings, cost and GHG emissions [32]. The IS retrofit approach focuses on the simultaneous retrofitting of multiple building systems [22]. By recognizing the interactive effects a load component such as a façade or lighting system, has on HVAC system equipment sizing and energy use, holistic IS strategies can be developed that achieve the multiple aims of energy and overall performance improvement. For example, designing better shading strategies can result in reduced cooling loads to the point where smaller cooling equipment can be used. IS may also enable the use of a technology that otherwise would not have been possible due to its lower cooling output, or perhaps the active cooling can even be eliminated. The cost savings of a downsized cooling system can offset the incremental cost of the load reducing measures. Similar opportunities exist for integrated benefits on other systems, such as heating and lighting retrofits. IS retrofits can also enable a range of additional non-energy benefits in the process, which further improve the overall attractiveness to customers [17]. IS retrofits allow for the reduction and optimization of equipment sizes when multiple building systems and assemblies are replaced simultaneously [22]. For success, engineers and contractors need to expand their skill set to focus on load reduction measures that allow for efficiency improvements with avoided capital costs. More than simply upgrading systems, IS retrofits require analysis and optimization for coordinated energy savings benefits gained from the interactions between systems, such as daylighting systems, alternative mechanical HVAC systems, envelope measures and other load reduction improvements [18]. Fluhrer *et al.* [32] compared the typical retrofit process by ESCOs with the IS retrofit process used in the Empire State Building. The main differences included (1) the IS retrofit approach investigates an extensive number of ECMs and the theoretical minimum energy use as the primary reference target, (2) the IS retrofit approach evaluates opportunities both for the building core services and in tenant spaces, which is rare in typical tenant-occupied retrofits, (3) the IS retrofit approach proposes a sophisticated yet reasonable business case to compel the owner to push for deeper energy savings. Harrington and Carmichael [33] described the detailed IS retrofit measures implemented in the Empire State Building. All windows were replaced with high performance windows, which cut winter heat loss by at least two-thirds and summer heat gain by half. The advanced glazing, improved lighting and office equipment cut the building's peak cooling load by one-third, which contributed to an estimated 38% whole building energy savings. Notably, the original retrofit plans included upgrading the existing chiller plant with new chillers to provide a needed increase in cooling capacity. However, the reduced cooling load due to the above measures enabled the existing chiller plant to be viable to serve the building, with a less intensive retrofit involving the reuse of the existing chiller shells and replacement of the chiller tubes, valves and motors. This effort saved the project more than $17 million [33], which in turn helped to fund the glazing and lighting upgrades throughout the building. This study however, did not quantify the benefits of the IS retrofit over the traditional retrofit approach of existing equipment replacement and upgrade. Quantification is critical in providing a direct understanding of exactly how the IS retrofit approach compares to traditional retrofit approaches. This is critical in helping building owners, engineers and contractors make informed decisions to enable deeper levels of energy savings, cost effectively.

This paper presents a case study quantifying the benefits of the IS retrofit approach over traditional incremental retrofit approaches, applied to an existing commercial building located in Hawaii, USA. The ECM solutions focused on building envelope, lighting and HVAC systems with the energy savings, energy cost savings and Life Cycle Cost (LCC) savings quantified. Detailed simulation results provide further insights for designers, engineers, contractors and building owners to guide in the selection of the best retrofit approach.

2. Methodology

2.1 Overview

This study considers two traditional retrofit approaches, a Standard Practice and an Improved Practice, in comparison with the IS retrofit approach. The Standard Practice approach entails replacing low performing existing equipment with a newer version of the same equipment that meets the minimum efficiency requirements prescribed by ASHRAE Standard 90.1-2013 [34]. The Improved Practice approach focuses on replacing the existing equipment with a newer version of the same equipment that has a higher efficiency (beyond ASHRAE Standard 90.1-2013 [34]), utilizing the latest technology available at the time of this study. Both approaches are considered non-integrated retrofit strategies because they ignore opportunities to retrofit the building systems that would have been beneficial to load reduction or to create synergistic combined system approaches. The IS retrofit goes beyond simple equipment swap-out. The IS approach considers ECMs that in combination allow for deeper energy savings than individual measures would have been able to achieve in isolation. In this way, the IS retrofit approach is able to unlock greater energy savings.

A simulation study was performed to calculate and analyze the energy saving benefits of the IS approach compared with the Standard Practice and the Improved Practice retrofits. The simulation was based on a real building from a retrofit project study of the Commercial Building Partnerships (CBP), a public/private cost-shared research and development program sponsored by the U.S. Department of Energy (DOE). The CBP program matched select commercial building owners and operators with representatives at U.S. National Laboratories, and the private sector. These teams explored energy-saving measures and approaches to achieve on the order of 50% energy savings and greater and apply them to specific commercial building projects.

An IS retrofit design was created for this case building in 2012, specifying technological improvements in building systems with state of the art approaches at that time. Design teams developed original energy models of the building and used them to evaluate energy savings of retrofit measures. At the time of publication, these designed retrofit measures had not yet been implemented in the building, so the energy savings from the IS retrofit are estimated from whole-building performance simulation, which used energy models with adjustments to enable apple-to-apple comparisons between the IS retrofit and traditional retrofit approaches. However, the IS retrofit measures were designed in detail by engineers, with a complete set of architectural, electrical, mechanical design specifications and drawings. A robust set of monitoring data was also used from the existing building to carefully quantify and characterize the existing building's performance and local conditions. The investment cost of each measure was also estimated by professionals. Using energy savings data along with these investment costs, the energy cost savings and LCC savings could be accurately simulated to quantify the benefits of the IS retrofit approach over traditional retrofit approaches.

Economic analysis was performed to evaluate and compare the economic benefits of the three retrofit approaches, focusing on energy cost and LCC savings. The well-developed Discounted Cash Flow (DCF) method was used to calculate the energy cost savings, using energy savings from simulation results used as inputs. The method of calculating the LCC savings assessment was similar, except that the investment cost of the ECMs were estimated and included along with the energy cost savings. Two different evaluation periods were considered for LCC analysis: 20 and 30 year timeframes. For the Standard Practice and the Improved Practice retrofit approaches, their ECMs were staggered and implemented individually in year 1 and year 10 (Table 2) to represent the current staggered condition of component based improvements. For the IS approach all IS ECMs were assumed to be implemented simultaneously in year 1, which would represent a single, holistic view towards integrated system design and implementation.

EnergyPlus Version 6.0 was chosen as the simulation tool for the case study. EnergyPlus is an open source program that models heating, ventilation, cooling, lighting, water use, renewable energy generation and other building energy flows [35] and is the flagship building simulation engine supported by the United States Department of Energy. It includes many innovative simulation capabilities including sub-hourly time-steps, modular systems and central plants, integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, natural ventilation, and user customizable energy management systems. Each release of EnergyPlus is continually tested extensively using more than four hundred example files, with test cases defined per ASHRAE Standard 140 [36]. EnergyPlus is a powerful tool that supports building professionals, scientists and engineers in optimizing building design and operations, and thus helps to reduce energy consumption. In this study, the weather file used consisted of TMY data from the Honolulu Airport. The HVAC systems were automatically autosized by EnergyPlus, with February 21 selected as the winter design day and August 21 selected as the summer design day.

2.2 Building details for the case study

The existing building selected for the case study was Kuykendall Hall, located on the University of Hawaii Mānoa (UHM) campus, in Honolulu (Figure 1). Honolulu belongs to ASHRAE climate zone 1A and experiences a tropical hot semi-arid climate per Köppen–Geiger classification with a mostly dry summer season. The cooling degree day, with the base 10°C (50°F, namely CDD50), is 9949, while the heating degree day, with the base 18.3°C (65°F, namely HDD65), is 0.

This case building was the focus of a CBP analysis and design collaboration between the University of Hawaii, their design consultants (Benjamin Woo Architects), and Lawrence Berkeley National Laboratory (LBNL) and their energy consultants (Loisos and Ubbelohde) [37]. The building has a total floor area of approximately 6874 m^2 (74000 ft^2), with about three quarters of the floor area consisting of a 4-story classroom wing [5017 m^2 (54000 ft^2)] and a quarter of the floor area consisting of a 7-story office wing [1858 m^2 (20000 ft^2)]. The 2nd floor plan is shown in Figure 2. The classroom wing is served by a fan-coil system with a central chiller plant, while the office wing is served by Packaged Terminal Air-Conditioners (PTACs).

Figure 1. The different facades of the building modeled in the case study.

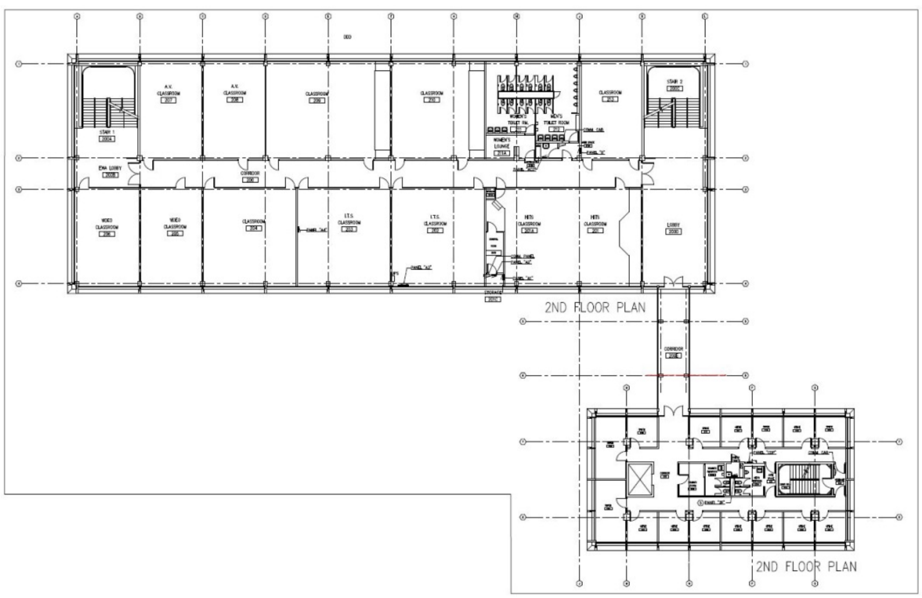

Figure 2. Plan of the 2nd floor.

2.3 Assumptions and modeling of the three retrofit scenarios

In this case study, the building and end use systems of interest are (1) lighting and plug load systems, (2) the building envelope and, (3) the HVAC system, with each having a strong interaction and influence on the whole building performance. For example, the lighting and plug load system contributes to the internal heat gain, affecting the cooling and heating loads of the HVAC system; the envelope and glazing system determines the envelope heat gain, which affects the cooling and heating load of the HVAC system; meanwhile, the window's visible transmittance (VT) determines the visible light through the window, affecting the lighting system's energy use and visual comfort, through use of daylight dimming control.

As a part of CBP, an IS strategy was developed to retrofit both wings and included the following upgrades: (1) the lighting system was redesigned entirely, including a new light fixture layout, new light fixtures with lighting types and locations selected for their performance in the new design, added daylighting and dimming controls; (2) the plug loads were planned for replacement with higher efficiency products; (3) the glazing was resized and replaced to have a lower U-factor, Solar Heat Gain Coefficient (SHGC) and higher visible transmittance, to enable adequate view and area for daylighting purposes; (4) extensive exterior shading systems were designed and optimized to eliminate direct solar heat gain into the space over the full course of the year while also enabling effective daylighting; (5) consequently internal gains and heat loads enabled the existing HVAC system to be replaced by a natural ventilation system coupled with a nighttime refrigerant based dehumidification system. The lighting system was redesigned to be replaced, to reduce the number of fixtures, provide fixture types and light sources selected for high performance and provide more efficient light distribution in the spaces. Light sources with higher efficiency, such as T5 and LED, were planned instead of the original T8 fixtures. While T8 lamps provide greater efficiency in terms of lumens/watt of energy use than a T5, the smaller diameter of the T5 allows a well designed luminaire to more effectively and efficiently illuminate a space resulting in fewer fixtures. About 90% of the redesigned fixtures in the classroom wing were planned for installation with T5 lamps and 10% were LED, while in the office wing the T5 and LED upgrades were 50% and 50%, respectively. At the time of the IS design, these were the prevailing cost effective high efficiency lighting strategies available. It is expected that the IS retrofit design would be further improved over the results presented due to recent advances and cost reduction in LED technology. About half of all of the existing plug load equipment were replaced by new and more efficient products, bringing down the equipment power density from an average of 13.1 W/m^2 for the classroom wing and 17.0 W/m^2 for the office wing to 5.4 W/m^2 and 11.2 W/m^2, respectively. The internal heat gains were sharply reduced by redesigning the lighting system, adding daylight dimming controls and improving the efficiency of plug loads. Meanwhile, the upgrades to the glazing and exterior shading system reduced the heat gains through the envelope and eliminated direct solar heat gains through the windows. The higher visible transmittance also enabled the application of daylighting deep into the space. The advanced shading system was designed to eliminate direct solar heat gain into the building over the entire course of the year, dramatically reducing cooling loads while improving thermal comfort. The combined retrofit on the lighting and envelope systems dramatically reduced the cooling loads. The existing HVAC systems for both wings were removed, and a natural ventilation system coupled with a nighttime dehumidification system was designed. Importantly, it should be noted that the new natural ventilation system would not be a feasible choice to meet the comfort needs of occupants without the retrofit of the envelope, lighting and plug loads that significantly reduced the cooling loads and direct solar gain on occupants. This combination of enabling system choices resulted in a viable combined IS approach for the building retrofit design. In the absence of a whole building IS strategy, the HVAC system would have continued to require the use of refrigerant based mechanical cooling, such as the chilled water and Packaged Terminal Air Conditioning (PTAC) existing systems.

For the Standard Practice retrofit approach analysis, the HVAC systems were renovated in the first year, where the fan-coil system chiller for the classroom wing and the PTACs for the office wing were upgraded to comply with the minimum efficiency requirement of ASHRAE Standard 90.1-2013 [34]. A water-cooled screw chiller with the minimum COP of 5.56 (0.634 kW/ton) was selected from a vendor catalog for the classroom wing. Two types of PTAC, 3520W capacity with a coefficient of performance (COP) of 3.02 and 2640W capacity with a COP of 3.28, were also selected from another vendor catalog to meet the zone loads of the office wing. In the 10th year, lighting and plug load systems were retrofitted. The existing light fixtures had their T8 lamps replaced with T5 lamps, which represent the equivalent code minimum LPD per ASHRAE 90.1-2013. Plug loads are not currently regulated by energy codes such as ASHRAE 90.1 [34], and as a result the plug load system remained as the existing system for the Standard Practice retrofit. The effects of improved plug load efficiency were however studied as part of the Improved Practice retrofit approach. Envelope retrofits have high installation costs and are typically very disruptive of normal operation. It is not a common practice to conduct envelope upgrades, such as glazing or insulation improvement, on a component level basis except at end of life for these building features, which typically occur on the 30 to 50 year timescale, outside the timeframe of the LCC study. Thus envelope related ECMs were not considered for the Standard or Improved Practice retrofit approaches. HVAC retrofit is proposed before the lighting retrofit due to two considerations: (1) the addition of the DOAS system as part of the HVAC retrofit will improve the humidity control, which is a priority of the building owner, (2) baseline lighting system has a mix of T8 and T5, which are relatively efficient and don't need urgent replacement.

For the Improved Practice retrofit, the HVAC systems were renovated in the first year. The classroom wing included an upgraded higher efficiency chiller with the minimum COP of 7.25 (0.484 kW/ton), based on a high efficiency water-cooled centrifugal chiller with VSD. The PTAC systems for the office wing were upgraded with high efficiency PTACs as well. Two types of high efficiency PTAC, 3520W capacity with a COP of 3.49 and 2640W capacity with a COP of 3.7, were selected for the office wing. The lighting and plug loads retrofits were conducted in the 10th year. The staggering of these retrofits is consistent with the incremental approach to technology switchouts that typically occur in existing buildings. The number of lighting fixtures and their layout is the same as the IS retrofit. Consistent with the rapidly improving lighting technologies market, all of the lamps were replaced with LED, which represents an improved lighting design over that included in the IS effort. Daylight dimming control was also included, similar to the IS strategy. For the plug load retrofit, existing equipment was replaced with higher efficiency products. The overall equipment power density was reduced to the same level as the IS retrofit.

Three sets of EnergyPlus models were developed representing each of these three retrofit scenarios. The detailed assumptions of the baseline model and the three retrofit models are shown in Tables 1 and 2. The baseline building model represented the existing building condition prior to retrofit with some minor variations to ensure that the model was representative of a thermally comfortable and well ventilated condition, per current code. These adjustments were considered necessary to ensure a fair comparison of each model representing a comfortable and code compliant condition. For example, in the existing building the outdoor air was not conditioned in the classroom wing and the indoor humidity was not controlled in both wings. As a result, thermal comfort was demonstrated to be usually unsatisfactory. Consequently, the baseline existing building model was slightly modified from the existing building conditions to provide humidity control and incorporate conditioned outside air where appropriate. For this, a Dedicated Outdoor Air System (DOAS) system was added to the central fan coil system for the classroom wing and reheat coils were added to the HVAC system for the office wing. The modified model was then used as the initial baseline model to compare against and quantify the benefits of the three retrofit approaches. The costs of these adjustments were not included in the retrofit comparison analysis. The simulated three scenarios then provided the energy consumption and energy savings of each retrofit approach.

Table 1. ECM description and modeling assumptions of the three retrofit approaches for the classroom wing.

ECMs description				Modeling assumptions				
	Integrated System	Standard Practice	Improved Practice		Existing Building	Integrated System	Standard Practice	Improved Practice
HVAC system	Year1: Change HVAC type and improve energy performance	Year1: Increase HVAC efficiency, no system type change		HVAC system	FanCoil System Chiller COP: 4.9	Natural Ventilation + Nighttime dehumidification (DX Cooling Coil COP: 3)	FanCoil System Chiller COP: 5.55	FanCoil System Chiller COP: 7.27
Lighting and Plug load	Year1: => Decrease lighting and equipment power density; => Add daylight dimming control	Year10: Decrease lighting and equipment power density	Year10: => Decrease lighting and equipment power density; => Add daylight dimming control	Lighting Power density (W/m^2)	20.5	5.9	11.8	4.4
				Equipment Power density (W/m^2)	13.1	5.4	13.1	5.4
Envelope	Year1: => Improve thermal properties of exterior wall and window; => Increase thermal mass	N/A		U-factor of exterior wall (W/m^2·K)	2.326	0.818	N/A	
				U-factor of interior wall (W/m^2·K)	2.006	1.414		

	of interior wall; **=> Upgrade shading system**		**U-factor of exterior window ($W/m^2 \cdot K$)**	**2.72**	**1.635**	
			SHGC	**0.764**	**0.388**	
			Shading system	**Profile angle of 54° on both South and North facades, and 2'-3" fins spaces 20' O.C.**	**Undulating horizontal louvers, and 4'-2" fins spaced 20' O.C.; Adjustable profile angles**	

Table 2. ECM description and modeling assumptions of the three retrofit approaches for the office wing.

ECMs description				Modeling assumptions				
	Integrated System	Standard Practice	Improved Practice		Existing Building	Integrated System	Standard Practice	Improved Practice
HVAC system	Year1: Change HVAC type and improve energy performance	Year1: Increase HVAC efficiency, no system type change		HVAC system	FanCoil System Chiller COP: 4.9	Natural Ventilation + Nighttime dehumidification (DX Cooling Coil COP: 3)	PTAC DX Cooling Coil COP: 3.02/3.28 (different capacity)	PTAC DX Cooling Coil COP: 3.49 /3.72 (different capacity)
Lighting and Plug load	Year1: => Decrease lighting and equipment power density; => Add daylight dimming control	Year10: Decrease lighting and equipment power density	Year10: => Decrease lighting and equipment power density; => Add daylight dimming control	Lighting Power density (W/m^2)	21.1	7.0	11.8	6.0
				Equipment Power density (W/m^2)	17.0	11.2	17.0	11.2
Envelope	Year1: => Improve thermal properties of exterior wall and window; => Increase thermal mass	N/A		U-factor of exterior wall ($W/m^2 \cdot K$)	2.326	0.818	N/A	
				U-factor of interior wall ($W/m^2 \cdot K$)	2.006	1.414		

	of interior wall; => Upgrade shading system		**U-factor of exterior window ($W/m^2 \cdot K$)**	**2.72**	**1.635**	
			SHGC	**0.764**	**0.388**	
			Shading system	**Profile angle of 70°on all facades, and 3’-10” fins spaced at 10’ O.C.**	**Horizontal louvers, and 1’-1” fins spaced at 10’ O.C.; Adjustable profile angles**	

2.4 Analysis of energy cost savings and Life Cycle Cost (LCC) savings

To evaluate and compare the economic benefits of these retrofit approaches, the analysis of both energy cost savings and LCC savings were performed. For energy cost savings, the Discounted Cash Flow (DCF) method was adopted. In this method, future cash flows, representing the energy cost savings that occur during the lifetime of the investment, are discounted to present time values and thus made comparable to today's investment expenditures. The DCF analysis, commonly used by investors, is a quantitative basis for rational decision making. The DCF method yields the indicator of the Net Present Value (NPV), derived from equation (2), where cf_t is the cash flow at year t (positive for earnings, negative for expenditures), T is the useful life of the investment in years and i is the discount rate [38].

$$NPV = \sum_{t=0}^{T} cf_t(1+i)^{-t} \tag{2}$$

In our case cf_t represents the annual energy cost savings associated with the ECMs, and T the useful life of the ECMs. Life cycle cost (LCC) is a standard engineering economic approach for choosing between alternative products or designs that provide roughly equal service to the user. LCC consists of two main components: (1) the first cost of buying and installing the equipment and (2) the operating cost over the lifetime of the equipment. As described in equation (3), LCC is defined as the investment cost of ECMs added to the NPV [39,40]. The investment cost includes the equipment cost and installation cost, and is represented as a negative input. If the LCC is greater than zero overall, the ECM investment cost is paid back within the useful life of the investment. Otherwise, the investment made for the ECM would not be paid back within the ECM lifetime. In this paper, LCC over 20 and 30 years are used as the metrics for comparing the cost savings of the three retrofit approaches.

$$LCC = ECM\ investment\ cost + NPV \tag{3}$$

Another influencing factor on the overall cost and value of the ECMs is the escalation of the energy price. In the case building, electricity is the only energy source. The historic electricity retail prices of Hawaii State (1990-2014) per EIA have a projected annual escalation rate of 5.6% [41], as shown in Figure 3. Referring to the CBP project report of the case building [37], a 5% discount rate is used in the NPV calculation. The commercial utility rate for Hawaii was \$0.3432/kWh in 2014, at the time of this study [41]. Assuming Year 1 for the retrofit approach comparison is 2016, the utility rate for 2016 would be \$0.3827/kWh. Two different evaluation periods, $T = 20$ and $T = 30$, were considered in the analysis.

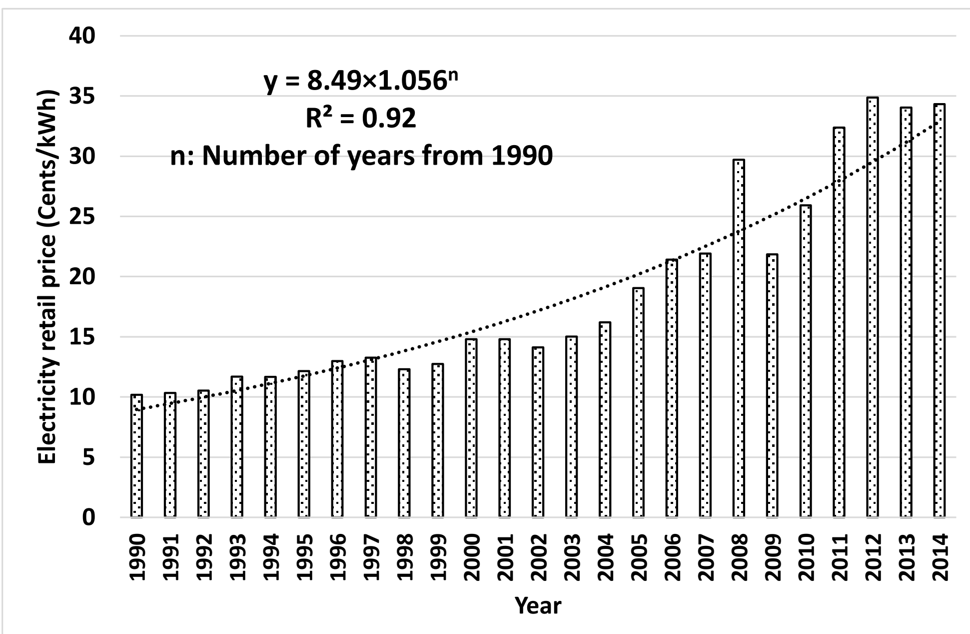

Figure 3. The projection of the escalation rate of electricity retail price in Hawaii State

All the ECM investment costs for the IS retrofit design were evaluated by professionals during the CBP project (Table 3). The ECM investment costs for the two traditional retrofit approaches have been estimated based on several sources: (1) RSMeans Online Mechanical Cost database

2015 [42], (2) RSMeans Electrical Cost Data book 2014 [43], (3) RSMeans Electrical Cost Data book 2010 [44], (4) DOE CALIPER program report [45], and (5) quotes from HVAC manufacturers as of July 2015. These costs are shown in Tables 4 through 7. All costs include materials and installation. The costs for the Standard and Improved Practice retrofit measures however do not include shipping costs, which serve to somewhat lower the costs for these approaches.

Table 3. Cost of ECMs in the Integrated System (IS) retrofit

ECMs description	**Cost**
New light fixtures	$636,140
Daylight dimming photosensors	$48,910
Control systems for both lighting and plug load	$588,865
New classroom glazing	$1,208,928
Roll down shades	$353,742
Exterior shading	$1,027,500
Window actuators	$507,150
Acoustic attenuation equipment	$2,701,730
Natural ventilation duct controls	$186,400
Classroom first floor conditioning	$270,000
Classroom exhaust fans	$24,000
Classroom dehumidification system	$400,000
Storm proof wall louvers	$414,975
Ceiling fans	$217,740
Remaining Office System	$675,600
Total	$9,261,680

Table 4. Cost of HVAC ECMs for the Standard Practice retrofit

Chiller						
Equipment	COP	Price	Labor Fee	O&P	Number of units	Total
250 ton (879 kW) screw water-cooled chiller	5.56	$100,000	$14,800	$18,000	1	$132,800
PTAC						
Equipment	EER	Price	Labor Fee	O&P	Number of units	Total Cost
PTAC 3520 (W)	10.3	$584/unit	$215/unit	$260/unit	12	$12,703
PTAC 2640 (W)	11.2	$558/unit	$172/unit	$213/unit	86	$81,132
Total HVAC equipment cost						$226,635

Note: O&P: Overhead and Profit

Table 5. Cost of lighting ECMs for the Standard Practice retrofit

Luminaire Material cost	**Luminaire replacement Labor cost**	**O&P**	**Number of Fixtures**	**Total cost**
$35.25	$6.55	$3.80	2,054	$93,662

Table 6. Cost of HVAC ECMs for the Improved Practice retrofit

Chiller						
Equipment	COP	Price	Labor Fee	O&P	Number of units	Total
250 ton (879 kW) centrifugal water-cooled chiller	7.25	$205,000	$13,300	$16,300	1	$234,600
PTAC						
Equipment	EER	Price	Labor Fee	O&P	Number of units	Total Cost
PTAC 3520 (W)	11.9	$607/unit	$215/unit	$260/unit	12	$12,985
PTAC 2640 (W)	12.7	$584/unit	$172/unit	$213/unit	86	$83,360
Total HVAC equipment cost						$330,945

Table 7. Cost of lighting ECMs for the Improved Practice retrofit

New LED fixtures and installation	**Daylight dimming photo sensors**	**Lighting and plug load control system**	**Total cost**
$663,366	$48,910	$588,865	$1,301,111

3. Results

3.1 Energy savings

Using the three sets of EnergyPlus models developed in section 2.3, the energy consumption of the baseline model and the three retrofit approaches were simulated. Since electricity is the only energy source in the case building, it will be used in the following results analysis. The detailed results of energy savings from each scenario are described in sections 3.1.1 to 3.1.3, and summarized in section 3.1.4.

3.1.1 The Integrated System retrofit approach

Figure 4 shows the total electricity savings of the IS retrofit broken down into HVAC, lighting and plug load categories. The results indicate roughly an 84% energy savings obtained by using the IS retrofit approach. The main contributors towards this savings include the reduction in the internal loads due to the retrofit of the lighting and plug load systems as well as the upgrades conducted on the building envelope which dramatically improved daylighting while eliminating direct solar gain over the course of the year. The reduction in internal loads and direct solar gain further enabled the removal of the previous HVAC system, and the installation of a natural ventilation strategy coupled with a nighttime dehumidification system. This change in technology significantly helped in reducing the total energy used.

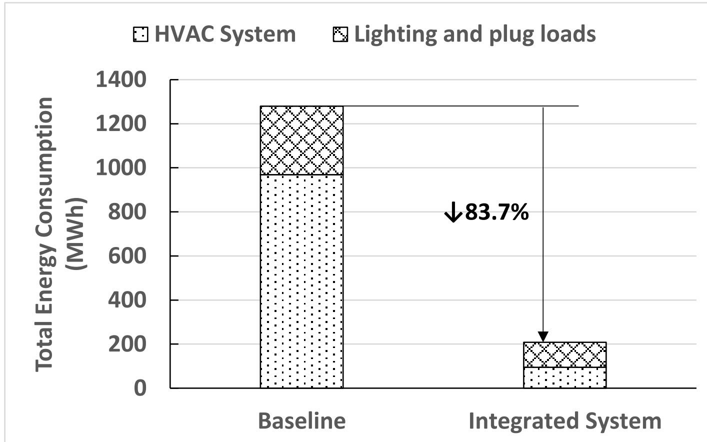

Figure 4. Energy savings of the IS retrofit approach.

3.1.2. The Standard Practice retrofit approach

Figure 5 shows the energy savings achieved by using the Standard Practice retrofit approach. The energy savings from upgrading the HVAC system conducted in Year 1 is 5.8%, and the energy savings from upgrading the lighting & plug loads systems in Year 10 is 6.7%. Total energy saving is 12.5%.

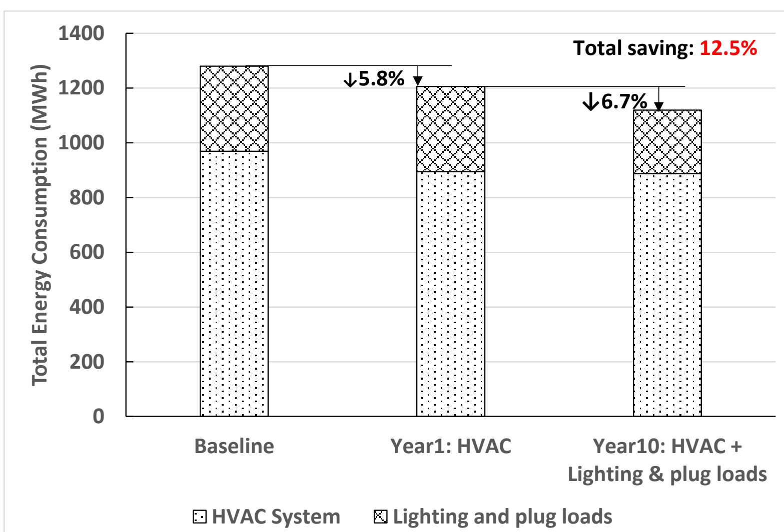

Figure 5. Energy savings of the Standard Practice retrofit approach.

3.1.3 The Improved Practice retrofit approach

Figure 6 shows the energy savings achieved from the Improved Practice retrofit approach. The energy savings from upgrading the HVAC system in Year 1 is 16.1%, and the energy savings from upgrading the lighting and plug loads system in Year 10 is 16.6%. Total energy saving is 32.7%.

Similar to Figure 5, the lighting & plug loads upgrade didn't result in significant decrease in HVAC system consumption in Year 10. This is mainly because the lighting & plug loads upgrade not only decreases the cooling need, but also increases the reheat energy, which is used to reheat supply air to control humidity. Therefore, the overall HVAC consumption didn't decrease significantly.

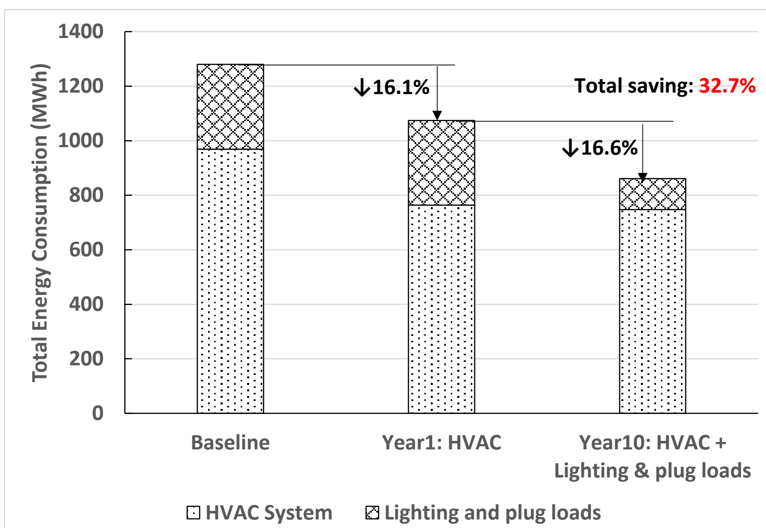

Figure 6. Energy savings of the Improved Practice retrofit approach.

3.1.4 Summary of energy savings

Table 8 and Figure 7 show the energy savings relative to the baseline model for all three retrofit scenarios. The Standard Practice retrofit, Improved Practice retrofit, and IS retrofit showed improvements over the baseline, with 123%, 33% and 84% savings, respectively. In the EUI metric, the Standard Practice retrofit, Improved Practice retrofit, and IS retrofit reduced the baseline EUI of 186 kWh/ m^2.yr to 163, 125 and 30 kWh/ m^2.yr, respectively.

Table 8. Energy consumption and savings from the three retrofit approaches compared with the baseline

	Baseline	Standard Practice	Improved Practice	Integrated System
Total Energy Consumption (MWh/yr)	1,278	1,119	861	208
Energy Saving (MWh/yr)	n.a.	160	419	1,071
Energy Saving (%)		13%	33%	84%
Energy Use Intensity (EUI) (kWh/m^2.yr)	186	163	125	30

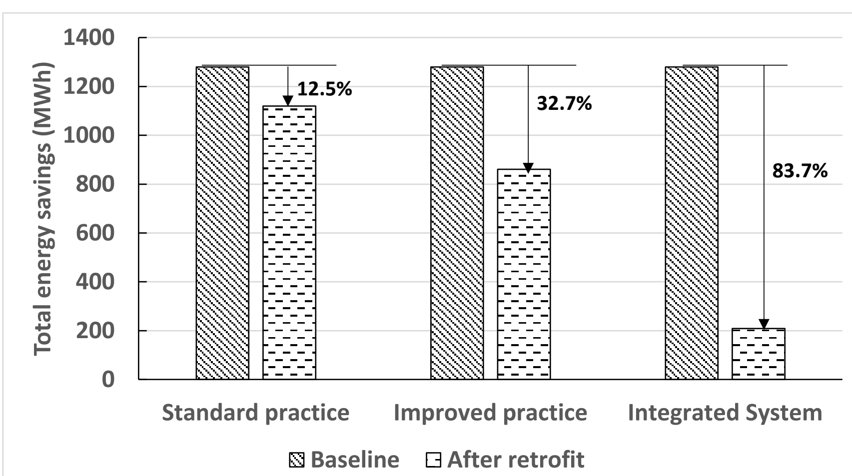

Figure 7. The energy savings of all three retrofit approaches

Figure 8 shows the breakdown by end use of the energy savings for both the baseline model and the retrofit approaches. From an energy savings perspective, the IS retrofit demonstrates a significant advantage over the two traditional retrofit scenarios, particularly for cooling consumption (including cooling equipment, fans and pumps), heating consumption and heat rejection. It is noted that the fans and cooling towers are consuming much less energy than other end-use categories while the pumps are consuming much more. The classroom wing is conditioned by a fan-coil system and the office wing is conditioned by PTAC; both of them are using small fans with minimum pressure drop. In contrast to traditional fan-coil systems that are usually connected to a central air-handling unit to provide outside air and pre-conditioned air, this system is distinct in that the fan coils are standalone units, with no connection to a central air handling system. In contrast, typical central VAV systems, whose fans supply air throughout the building to each zone, have much longer air distribution systems, terminal devices to consider and consequently have a much larger air pressure drop and significantly higher fan energy. Therefore, fans in the existing fan-coil system and PTACs consume much less energy. While On the hydronic system, the existing fan-coil system circulates chilled water and hot water throughout the entire building using pumps, so pumps are one of the key energy consumers for this building. For the cooling tower, the main source of energy consumption is by its fans, and this building uses a two-speed cooling tower, which saves much energy especially at partial load conditions by operating at the low speed mode. Note that by fan laws there is an energy reduction of 7/8ths due to fan speed of 1/2 (there is a cubic relationship between the two).

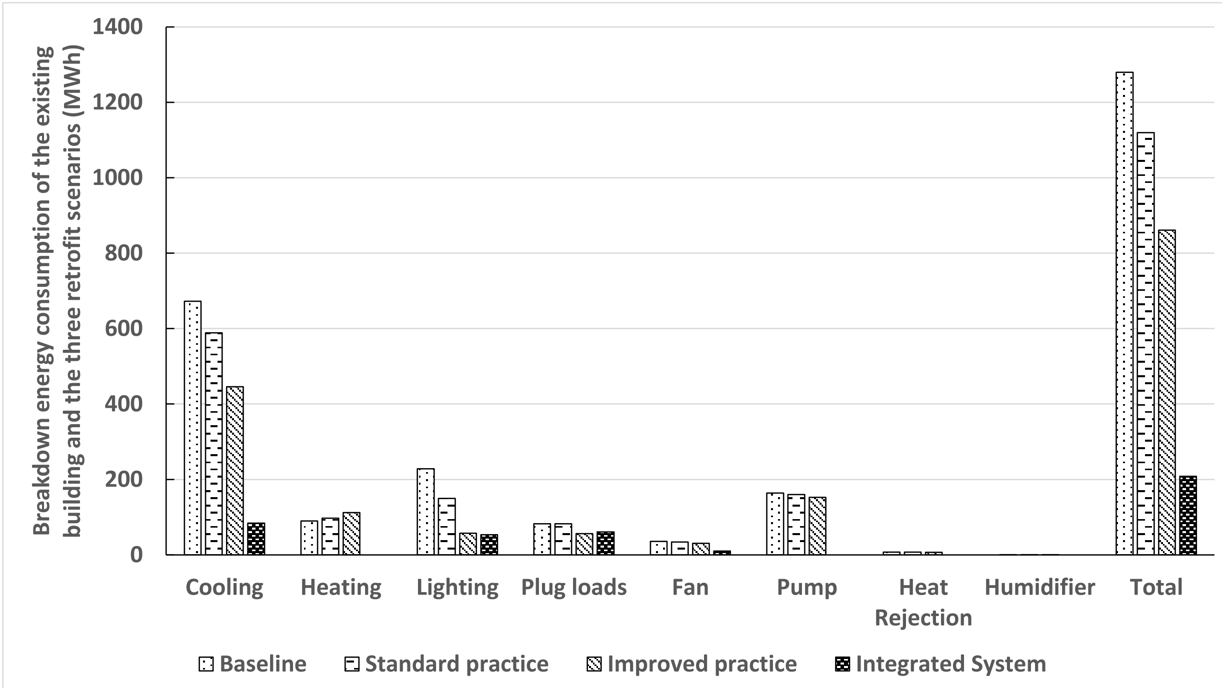

Figure 8. A comparison of the breakdown of electricity consumption between the existing building, the Standard Practice, Improved Practice and the Integrated System retrofit approaches.

When evaluating the breakdown of the end-use consumptions the baseline model consumes the most energy (except with heating), followed by the Standard Practice, the Improved Practice and then the Integrated System approach. The main use of heating in the baseline model, the Standard Practice and the Improved Practice, is reheat of supply air to control humidity. Reheat energy generally increases as the internal loads decrease. The IS retrofit does not have any heating energy due to the fact the natural ventilation system is able to meet the thermal comfort needs during the daytime and the dehumidification system (which does not include reheat) operates at night when the building is unoccupied.

As mentioned in ASHRAE Standard 55-2010 [46], occupants' thermal responses in naturally ventilated spaces depend in part on the outdoor climate and may differ from thermal responses in buildings with centralized HVAC systems. Therefore, typical thermal comfort indexes which can be applied to air-conditioned buildings, such as ASHRAE Standard 55's standard comfort range and PMV, are not the most suitable for naturally ventilated buildings, while ASHRAE Standard 55's adaptive comfort criteria can be generally applied to naturally ventilated buildings (the IS retrofit approach).

We compared the number of unmet hours for thermal comfort related to operative temperature, humidity (taking 70% as upper limit) and CO2 concentration of the baseline model and IS retrofit model. We used the ASHRAE Standard 55 standard comfort range for the baseline model and the adaptive comfort criteria for the IS retrofit model. As shown in Table 9, the IS retrofit approach can still produce relatively satisfying thermal comfort as well as slightly better indoor air quality (IAQ). The IAQ didn't improve more substantially because there are certain periods when the natural ventilation has to be turned off due to high outdoor air temperature.

Table 9. Comfort indexes comparison between the baseline and IS retrofit models

	Unmet hours of operative temperature	**Unmet hours of humidity**	**Average CO_2 concentration during occupied periods**
Baseline model	492	59	898
IS retrofit model	303	208	828

3.2 Cost savings estimation

Energy cost savings are calculated using the DCF method, based on the energy saving results from section 3.1, the utility rates (5.6% escalation per year) and a discount rate of 5%. The discount rate was used to adjust for risk, opportunity cost or other factors, making the energy cost savings more conservative. The investment costs of ECMs were obtained using a number of reliable sources (see section 2.4).

Figure 9 shows the ECM costs versus the energy cost savings. The results confirm that the Standard Practice retrofit costs the least and saves the least, while the Integrated System costs the most and saves the most. The energy cost saving of the IS retrofit is not as big as the ECM investment cost in the 20th year, but easily surpasses it in following years due to outstanding energy cost savings. In other words, with longer periods of building operation the benefits of the IS retrofit become more significant.

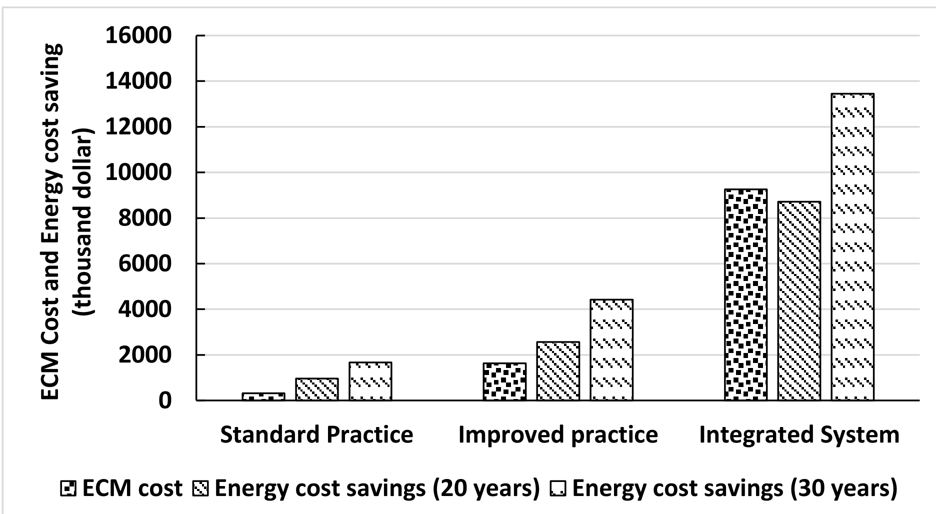

Figure 9. ECM cost and energy cost savings of the three retrofit scenarios.

The NPV over 20 and 30 years are used as the metrics for comparing the life cycle cost savings for the three retrofit approaches. Table 10 shows the ECM cost, the energy cost savings and the LCC savings for 20 year and 30 year periods. The results indicate that the LCC of the IS retrofit in the 20th year is negative. This means that the initial investment is not paid back by the 20th year. However, by the 22nd year LCC of the Integrated System turns positive signifying the potential for long-term benefits.

A notable part of the ECM cost in the IS retrofit of the Hawaii building was an investment of $2.7M towards the installation of acoustic attenuation on the natural ventilation intakes (See Appendix for cost details). Acoustic attenuation is used to reduce exterior noise to meet the acoustic comfort criteria inside the building. This requirement is specific to the location and may not be required to the same extent for ventilation intakes installed at other sites. In this campus environment, noise sources commonly include cars, mopeds, leaf blowers and outdoor music. Therefore, the initial investment cost may not always be as high as indicated in this case study. Without this investment, the cost savings of the IS retrofit would be much better; the LCC of the Integrated System in the 20th and 30th years would be around $2.1M and $6.9M, respectively, and the initial investment would be paid back in the 16th year. It should be noted that the payback period of the Improved Practice is 15 years, almost the same as the Integrated System. In other words, the Integrated System is showing a significant advantage.

Table 10. Cost summary for three retrofit approaches.

Cost metric	Standard Practice (thousand dollars)	Improved Practice (thousand dollars)	Integrated System (thousand dollars)	IS without acoustic attenuation (thousand dollars)
ECM cost	320	1,632	9,262	6,560
Energy cost savings (20 yrs)	964	2563	8710	8710
Energy cost savings (30 yrs)	1,673	4,417	13,452	13,452
LCC savings (20 yrs)	643	931	-552	2,150
LCC savings (30 yrs)	1,353	2,785	4,190	6,892

4. Discussion

4.1 Comparison between the three retrofit approaches

The IS retrofit approach compared against the two traditional retrofit approaches showed higher initial costs, but substantially higher energy savings (84%). At this deep level of energy savings, it became possible for the building to achieve zero net annual energy consumption, with energy production offset solely by building mounted photovoltaic panels, a feat that was not possible with the Standard or Improved retrofit approaches. This is further notable as an achievement given the multi-story configuration of both wings. The significant difference between the Integrated System retrofit approach and the traditional retrofit approaches is how the ECMs are selected and developed, the ability for new ECMs to become viable as a part of the integrated design, the ability for deeper levels of energy savings to be targeted by synergistic designs, as well as when they are implemented. The Standard Practice retrofit approach is the easiest strategy to implement with the least initial cost, but the overall energy savings are limited. The Improved Practice retrofit approach is similar to the Standard Practice retrofit in terms of timing of the ECM upgrades, but uses state-of-the-art technologies, including lighting systems improved over the IS case, resulting in greater savings than Standard Practice. The IS retrofit considers a holistic system upgrade, which requires a comprehensive design, significant up-front costs as well as an integrated implementation, but it has the greatest savings potential especially over long-term operation (20-30 years). The IS retrofit approach can become more cost effective in the short to medium term considering the further advances and reduced cost in available lighting technologies beyond those studied, as well as the avoidance of acoustic attenuation in some applications. It should also be noted as indicated earlier, that the IS retrofit design included 90% of the light fixtures as T5 lighting and 10% as LED lighting. It is expected that there would be additional energy and energy cost savings for this design if updated to current best practice LED lighting selections. LED lighting costs have come down significantly since this study, and both this factor as well as the increased energy cost savings would further improve the NPV of the system in the 20th and 30th years.

To make a fair comparison for other potential applications, the economic benefits are recalculated excluding the acoustic attenuation equipment from the installation cost. The revised results are shown in Table 10. The ECM investment cost of IS retrofit is sharply reduced from

$9,262k to $6,560k, resulting in significant LCC savings. The 20-year LCC savings for the IS retrofit approach in this case are more than double that of the Improved Practice retrofit; while the 30-year LCC savings are even greater. Overall, these results demonstrate a clear advantage of LCC savings for the IS retrofit over time.

4.2 Limitations

The life cycle cost analysis adopted in this paper doesn't include the embodied energy cost from the production and transportation phases of the ECM materials and technologies. This is because (1) current industry practice is to evaluate retrofit measures based on equipment cost and energy cost, not including embodied energy costs from production and transportation (2) it is difficult to get comprehensive embodied energy and transportation energy cost data for the current ECMs. However, it is recognized that from a greenhouse gas reduction perspective they are very important for complete life cycle energy analysis, and should be considered in the future research, especially when more data is available. On the other hand, non-energy benefits, such as the improvement of thermal comfort, indoor air quality and noise protection, are also a very important aspect of the retrofit measures although these were also not quantifiable at the time of publication. These non-energy benefits would further serve to improve the ROI of these ECMs. Though incorporating the production and transportation energy related costs may reduce the advantages of retrofit measures, evaluating and incorporating the non-energy benefits in future research would offset these additional costs to a certain level.

An additional substantial benefit to the value and longevity of the retrofit building is currently not captured in the presented analysis. In the IS retrofit a substantial upgrade to the building envelope was included that prolongs the useful life of the building. This value is currently not quantified or reflected in the LCC analysis. It is expected however that in the 30 to 50 year timeframe the Standard Practice and Improved Practice retrofit cases would eventually result in increased investment in the building envelope due to end of life performance issues as well. Overall, this will significantly improve the LCC position of the IS retrofit beyond the results shown.

For lighting and HVAC systems, we assumed their retrofits last till the end of the life cycle for the two retrofit scenarios (20 and 30 years). Considering the latest LED lighting and HVAC technologies, together with better maintenance practices, these retrofits will likely last several decades. Another limitation is that the cost associated with cooling tower water use is not considered.

It should be mentioned that the results of the cost saving analysis are sensitive to the discount rate as well as the energy price escalation rate. The discount rate is used to interpret the fact that the future energy cost savings are less valuable in present time terms. Likewise, with a higher energy price escalation rate, more energy cost savings could be obtained during the lifetime of the investment.

4.3 Barriers to the Integrated System retrofit

The Integrated System retrofit approach is a relatively innovative concept which is not yet being widely adopted. Besides the common barriers in traditional building retrofits mentioned in the Introduction, there are additional challenges for the Integrated System retrofit:

(1) Higher upfront investment cost and perceived longer payback periods: The IS retrofit approach usually costs more than traditional retrofits conducted over time due to its involvement of multiple building systems, including the envelope, incorporated as one effort upfront instead of staggered over years. Due to the higher upfront investment cost, IS retrofits usually have a longer payback period than traditional retrofits [47], but as

technology progress and costs decrease this gap will become smaller. Design teams may also be using first cost and simple payback in evaluating ECMs rather than life cycle cost analysis [18], making the higher initial investment cost appear less attractive. Capital upgrade analyses that can take into account comparisons with future expenses for building system retrofits as well as end of life envelope upgrades and repairs will be a key contribution towards making IS retrofits a readily recognizable economic advantage.

(2) Complexity: The systems in buildings are highly interactive. The loads contributed by the climate, envelope, lighting and plug loads determine what types of HVAC systems can be used. For example, if cooling loads are reduced to minimum, natural ventilation may be used in mild climates (e.g., San Francisco, USA) to provide indoor comfort rather than mechanical air-conditioning systems. In order to design a holistic retrofit strategy that minimizes energy use all systems must be considered together. Design teams should explore advanced technologies and their integration strategies to enable deeper energy savings. Due to these interactions, integrated envelope and internal load strategies can enable lower energy use technologies to become viable, such as natural ventilation and radiant cooling. The study and selection of the retrofit technologies can be complex [27].

(3) Lack of experience: The industry lacks experience with the processes and knowledge required to perform integrated systems deep retrofits [18].

(4) Retrofit analysis tools require expertise: There are a number of existing tools for building retrofit analysis [48,49], but most of them require a high level of expertise from professionals to evaluate IS retrofit strategies.

More practitioners are becoming aware of the deep energy savings achievable by Integrated System retrofits as green building programs such as LEED™ become more sought after by building owners and developers. The U.S. Department of Energy is also providing guidance on achieving deep, low energy building retrofits [22], as well as ASHRAE [50]. Additionally, the U.S. government and utilities are providing financial support, such as incentives and rebates, for energy saving retrofit projects. Convincing building owners to focus on medium to long term economic performance, and enabling economic assessments that compare against the business as usual cases over time is another key issue to implementing IS retrofits. Easy to use and advanced retrofit analysis tools will also enable design teams the ability to explore and evaluate Integrated System retrofit strategies. Finally, the advancement of energy saving building technologies will unlock deeper retrofit energy savings as well as reduced equipment investment cost, which will improve the economic payback of IS retrofits.

These barriers can be addressed by focusing on medium to long term energy savings and economic performance, by continuous cost reduction of low energy technologies such as LED lighting, as well as by providing easy to use retrofit analysis tools and developing best practice guidelines on Integrated System retrofits. It is recommended that the Integrated System approach be adopted in building retrofits to achieve much deeper energy savings beyond traditional retrofit practices.

4.4 Future research

Future research can address some of the major barriers in the design and application of integrated systems. This would include creating packages of integrated technologies to allow for more streamlined access and deployment, including through retrofit opportunities. Tools and processes to allow for the identification of cost effective opportunities would be beneficial, particularly to identify the tipping points of the removal or drastic size reduction of a system would unlock the capital expenditures to be spent on supporting energy efficiency improvement areas. Further barriers exist in the development and deployment of cost effective integrated controls strategies including the approaches to reduce the transactional effort needed to implement these strategies, such as creating open source communications platforms and packaged, validated controls sequences. Finally, a means of feedback in the deployment in these systems is crucial to ensure that design intent is being met in operations. Overall, deep, low energy retrofits as demonstrated through the Integrated System approach can be an important part of reducing energy and meeting broader energy and carbon emission reduction goals, while ensuring satisfactory building performance.

5. Conclusions

The Integrated System retrofit approach, demonstrated through the case study building at the University of Hawaii, enabled innovative, deep energy saving strategies by considering the correlation and interaction among the building's systems to target deep, holistic energy saving strategies. This was achieved by optimizing envelope and internal load systems to enable a much lower energy HVAC system selection while maintaining thermal comfort. This simulation study quantified the benefits of the Integrated System retrofit approach compared with two traditional retrofit approaches, the Standard Practice retrofit and the Improved Practice retrofit. Three sets of EnergyPlus models were developed representing the three retrofit approaches, which were used to determine their energy savings. The results demonstrate that the IS retrofit for the case study building saved 84% energy over the existing energy use of the building, while the Standard Practice and the Improved Practice approaches saved 12% and 33%, respectively. The Integrated System approach therefore has a significant advantage over the two traditional retrofit approaches in terms of energy savings. The Integrated System approach also demonstrated the most favorable life cycle cost savings over the medium to long term. Further reductions in initial investment costs will improve accessibility to the extraordinary energy savings of the IS retrofit, although IS retrofits are currently economically viable, especially from the aspect of long-term investment, and considering longer term investment in building retrofits and end-of-life improvements.

The main challenges to the wide adoption of the IS retrofit approach include higher upfront capital investment compared with the incremental cost in the traditional retrofit approaches, lack of experience with IS retrofits, and the significant expertise required to use the retrofit analysis and design tools. The longer payback period demonstrated in this study also poses an issue where the period is long enough that other retrofits would be considered in the building for programmatic or general upgrade purposes. While this may be true, this study does represent the most involved level of a building upgrade to enable a deep low energy result, where extensive work was done on the facades and all systems. Having established a foundation of passive and active strategies with this work, future upgrades would be less extensive in nature to maintain or even improve performance. For buildings not able to contribute to the higher upfront capital investment for the full IS strategy, there may be viable Improved Practice approaches that can combine some lighter elements of envelope retrofits to help reduce thermal loads, although perhaps not to the full extent of the IS approach illustrated here. In these cases efforts would contribute to reducing the thermal load and capacity of HVAC systems, although might not go so far as to replace the system type or existing distribution.

Acknowledgment

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We thank Sarah C. Taylor-Lange of LBNL for her help with editing.

References

[1] Energy Information Administration, Annual Energy Outlook, 2012.

[2] U.S. Department of Energy, Building Energy Data Book - Building Share of Electricity Consumption/Sales, 2011.

[3] Energy Information Administration, 2012 Commercial Building Energy Consumption Survey (CBECS) survey data, 2015.

[4] Energy Information Administration, 2009 Residential Energy Consumption Survey (RECS) survey data, 2011.

[5] McGraw Hill Construction, Smart Market Reports. Green BIM – How Building Information Modeling is Contributing to Green Design and Construction, 2010.

[6] J. Osborn, C. Goldman, N. Hopper, Assessing U.S. ESCO Industry: Results from the NAESCO Database Project. Lawrence Berkeley National Laboratory: LBNL-50304, 2002.

[7] IPCC, Climate change 2007: mitigation of climate change. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change, 2007.

[8] M. MacLeod, D. Moran, V. Eory, R.M. Rees, A. Barnes, C.F.E. Topp, et al., Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK, Agric. Syst. 103 (2010) 198–209. doi:10.1016/j.agsy.2010.01.002.

[9] F. Kesicki, N. Strachan, Marginal abatement cost (MAC) curves: Confronting theory and practice, Environ. Sci. Policy. 14 (2011) 1195–1204. doi:10.1016/j.envsci.2011.08.004.

[10] G. Kumbaroglu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy Build. 49 (2012) 327–334. doi:10.1016/j.enbuild.2012.02.022.

[11] F. Ardente, M. Beccali, M. Cellura, M. Mistretta, Energy and environmental benefits in

public buildings as a result of retrofit actions, Renew. Sustain. Energy Rev. 15 (2011) 460–470. doi:10.1016/j.rser.2010.09.022.

[12] M. Jaggs, J. Palmer, Energy performance indoor environmental quality retrofit - a European diagnosis and decision making method for building refurbishment, Energy Build. 31 (2000) 97–101. doi:10.1016/S0378-7788(99)00023-7.

[13] M. Beccali, M. Cellura, M. Fontana, S. Longo, M. Mistretta, Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits, Renew. Sustain. Energy Rev. 27 (2013) 283–293. doi:10.1016/j.rser.2013.05.040.

[14] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options, Build. Environ. 72 (2014) 82–101. doi:10.1016/j.buildenv.2013.10.018.

[15] K. Sun, D. Yan, T. Hong, S. Guo, Stochastic modeling of overtime occupancy and its application in building energy simulation and calibration, Build. Environ. 79 (2014) 1–12. doi:10.1016/j.buildenv.2014.04.030.

[16] K. Sun, T. Hong, A Simulation Approach to Estimate Energy Savings Potential of Occupant Behavior Measures, Energy Build. (2016) (Article in press). doi:10.1016/j.enbuild.2016.12.010.

[17] J. Amann, E. Mendelsohn, Comprehensive Commercial Retrofit Programs: A Review of Activity and Opportunities, in: ACEEE-A052, 2005.

[18] V. Olgyay, C. Seruto, Whole-building retrofits: A gateway to climate stabilization, ASHRAE Trans. 116 (2010) 244–251.

[19] A. Satchwell, P. Larsen, C. Goldman, Combining Energy Efficiency Building Retrofits

and Onsite Generation : An Emerging Business Model from the ESCO Industry Definition and Size of the U . S . ESCO Industry, in: ACEEE Summer Study Energy Effic. Ind., 2011: pp. 132–145.

[20] P.H. Larsen, C.A. Goldman, A. Satchwell, Evolution of the U.S. energy service company industry: Market size and project performance from 1990-2008, Energy Policy. 50 (2012) 802–820. doi:10.1016/j.enpol.2012.08.035.

[21] C.A. Goldman, N.C. Hopper, J.G. Osborn, Review of US ESCO industry market trends: An empirical analysis of project data, Energy Policy. 33 (2005) 387–405. doi:10.1016/j.enpol.2003.08.008.

[22] Pacific Northwest National Laboratory, Advanced Energy Retrofit Guides - Office Buildings, 2011. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20761.pdf.

[23] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings, Energy. 36 (2011) 5037–5052. doi:10.1016/j.energy.2011.05.050.

[24] H. Tommerup, S. Svendsen, Energy savings in Danish residential building stock, Energy Build. 38 (2006) 618–626. doi:10.1016/j.enbuild.2005.08.017.

[25] J. Kragh, J. Rose, Energy renovation of single-family houses in Denmark utilising long-term financing based on equity, Appl. Energy. 88 (2011) 2245–2253. doi:10.1016/j.apenergy.2010.12.049.

[26] MLIT (Ministry of Land, Infrastructure, Transport, and Tourism), Housing needs survey (in Japanese), 2003.

[27] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-

the-art, Energy Build. 55 (2012) 889–902. doi:10.1016/j.enbuild.2012.08.018.

[28] Climate Works Australia, Australian Carbon Trust Report: Commercial Buildings Emissions Reduction Opportunities, 2010.

[29] N. Stern, The Economics of Climate Change – The Stern Review, 2006.

[30] N. Stern, Key Elements of a Global Deal on Climate Change, 2008.

[31] U.S. Department of Energy, http://energy.gov/eere/efficiency/buildings, (n.d.).

[32] C. Fluhrer, E. Maurer, A. Deshmukh, Achieving radically energy efficient retrofits: The empire state building example, ASHRAE Trans. 116 (2010) 236–243.

[33] E. Harrington, C. Carmichael, RetroFit Project Case Study : Empire State Building, Rocky Mt. Inst. Case Study Database. (2009) 1–9. http://www.rmi.org/Content/Files/ESBCaseStudy.pdf.

[34] ASHRAE, ANSI/ASHRAE/IES Standard 90.1-2013: Energy Standard for Buildings Except Low-Rise Residential Buildings, 2013.

[35] D.B. Crawley, L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, et al., EnergyPlus: Creating a new-generation building energy simulation program, Energy Build. 33 (2001) 319–331. doi:10.1016/S0378-7788(00)00114-6.

[36] ASHRAE, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, Ashrae. 140–2001 (2014) 77.

[37] C. Regnier, A. Harding, A. Robinson, Achieving a Net Zero Energy Retrofit — in a humid, temperate climate — lessons from the University of Hawaii at Mānoa. Lawrence Berkeley National Laboratory: LBNL-189802, 2015.

[38] R. W. Amstalden, M. Kost, C. Nathani, D. M. Imboden, Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy

instruments and energy price expectations, Energy Policy. 35 (2007) 1819–1829. doi:10.1016/j.enpol.2006.05.018.

[39] J. Lutz, A. Lekov, P. Chan, C.D. Whitehead, S. Meyers, J. McMahon, Life-cycle cost analysis of energy efficiency design options for residential furnaces and boilers, Energy. 31 (2006) 311–329. doi:10.1016/j.energy.2005.02.002.

[40] G. Rosenquist, P. Chan, A. Lekov, J. Mcmahon, R. Van Buskirk, Consumer life-cycle cost impacts of energy-efficiency standards for residential-type central air conditioners and heat pumps, ASHRAE Trans. 108 Part 1 (2002) 619–30.

[41] Energy Information Administration, http://www.eia.gov, (n.d.).

[42] RSMeans Online Mechanical Cost database, (n.d.). https://www.rsmeansonline.com/.

[43] RSMeans Green Building Cost Data, (2014).

[44] RSMeans Electrical Cost Data, (2010).

[45] Pacific Northwest National Laboratory, CALIPER Report 21.3: Cost-Effectiveness of Linear (T8) LED Lamps, 2014.

[46] ASHRAE, ASHRAE STANDARD 55-2010: Thermal Environmental Conditions for Human Occupancy, 2010.

[47] L. Tobias, Retrofitting Office Buildings to Be Green and Energy-Efficient: Optimizing Building Performance, Tenant Satisfaction, and Financial Return, (2010) 308. http://www.amazon.com/Retrofitting-Office-Buildings-Green-Energy-Efficient/dp/0874201330/ref=sr_1_1?ie=UTF8&qid=1394278482&sr=8-1&keywords=green+retrofitting.

[48] T. Hong, M.A. Piette, Y. Chen, S.H. Lee, S.C. Taylor-Lange, R. Zhang, et al., Commercial Building Energy Saver: An energy retrofit analysis toolkit, Appl. Energy. 159

(2015) 298–309. doi:10.1016/j.apenergy.2015.09.002.

[49] S.H. Lee, T. Hong, M.A. Piette, S.C. Taylor-Lange, Energy retrofit analysis toolkits for commercial buildings: A review, Energy. (2015). doi:10.1016/j.energy.2015.06.112.

[50] ASHRAE, ANSI/ASHRAE Standard 100-2015: Energy Efficiency in Existing Buildings, Atlanta, 2015.