Using Energy Audit Methods and Computer-Based Modeling to Develop Energy Efficient Building Retrofit Strategies for Universidad Don Bosco

La utilización de métodos de auditoria energética y modelaje basado en computadora para el desarrollo de estrategias de modernización de energía eficiente en la Universidad Don Bosco

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Resumen

Este artículo presenta múltiples soluciones innovadoras para reducir el consumo energético en los edificios de la Universidad Don Bosco. Este artículo identifica las pérdidas críticas de energía en tres edificios de uso intensivo de energía de la UDB por medio de las prácticas de auditoría energética y el modelado por computadora. Se desarrollan innovaciones específicas de ahorro de energía usando el software de simulación de edificios eQuest. También se proponen múltiples opciones innovadoras para que los administradores universitarios tengan flexibilidad para seleccionar las soluciones más adecuadas en función de sus limitaciones presupuestarias y objetivos de eficiencia energética. Las tres innovaciones más favorables investigadas son: (1) la reducción de las tasas de infiltración en el *Edificio Dos,* (2) la aplicación de un techo fresco para *El Taller de Mecánia*, y (3) la actualización a SEER 13 de los equipos de refrigeración en el Taller de Mecánica. Se espera que estas modernizaciones sirvan para ahorrar 4,0 MWh/año (1), 5,5 MWh/año (2), y 28,9 MWh / año (3), respectivamente. Los períodos de amortización de los costos se pronostican en 7,1 años (1) , 7,7 años (2) y 7,0 años (3), respectivamente.

Palabras Clave: eficiencia energética, modernización, auditoria energética, modelaje eQuest

Abstract

This article presents multiple retrofit solutions to reduce energy consumption in the buildings of *La Universidad Don Bosco* (UDB) campus in Soyapango, El Salvador. This article identifies the critical energy losses in three energy intensive UDB campus buildings by means of energy audit practices and computer-based modeling. Specific energy saving retrofits were developed using the building simulation software eQuest. Multiple retrofit options are developed to provide university administrators with flexibility in selecting the most appropriate solutions based on their budgetary constraints and energy efficiency goals. The three most favorable retrofits investigated were: (1) reducing infiltration rates in *Edificio Dos*, (2) implementation of a cool roof for *El Taller Mecánico*, and (3) upgrading to SEER 13 cooling equipment in *El Taller Mecánico*. These retrofits are expected to save 4.0 MWh/year (1), 5.5 MWh/year (2), and 28.9 MWh/year (3) respectively and the discounted payback periods are forecasted at 7.1 years (1), 7.7 years (2), and 7.0 years (3), respectively.

Keywords: energy efficiency, building retrofits, energy audit, eQuest modeling

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The construction and operation of buildings consumes over a third of the world's energy production and 40% of all mined resources (Straube, 2006). It has been estimated that in developing nations, buildings account for 20-40% of total energy consumption (Perez-Lombard et al., 2008). Given that buildings comprise a large portion of global energy use, they have significant environmental impacts, which are most commonly seen in the forms of fossil fuel combustion, air pollution, production of greenhouse gases, and non-renewable natural resource consumption. According to a 2009 McKinsey feasibility analysis, improving energy efficiency in buildings is one of the most financially viable means for greenhouse gas abatement and often results in negative project costs over the long term. Additionally, investment in energy efficiency can lower energy bills, stabilize energy prices, reduce demand for fossil fuels, defer the need for new infrastructure, and help reduce air pollutants (EPA, 2008).

Electric Energy Consumption in El Salvador

From 2003 to 2009 the demand for electricity in El Salvador grew by an average of 3.9% per year (Barrera, 2011). During the same time period the average cost of electricity per kWh increased by 8.9% per year on top of the national inflation rate (SIGET, 2011). Due to the rising demand and cost of energy, it is crucial that *La Unversidad Don Bosco* (UDB) search for ways to reduce the energy consumption of the buildings on campus. El Salvador's current strategy for meeting incremental energy demand is to construct new power generation plants (mainly hydroelectric, but also the Cutuco Energy fossil fuel-based plants) and develop contracts with existing power producers in an attempt to guarantee a steady energy supply at reasonable prices (CEL, 2008). However, UDB has the potential to create an independent energy security plan by implementing energy efficiency measures within the university campus. Improved energy efficiency in buildings on the UDB campus would reduce dependency on outside energy sources. Less money spent on energy could also help maintain reasonable tuition costs and avoid possible budget cuts.

The Latin American Energy Association (OLADE) estimated in 2008 that El Salvador's electricity sector (geothermal, hydroelectric, bunker fuel-fired, and biomass plants) emitted 3.3 million metric tons of carbon dioxide equivalent (CO_2e) into the atmosphere, which translates to roughly 592 metric tons CO_2e/GWh generated (OLADE, 2009). UDB's main campus consumes about 965 MWh annually, which results in emissions of roughly 571 tCO_2e each year. Electricity is the sole form of energy delivered to all classrooms and offices on the UDB campus, and propane is only consumed in significant quantities in the cafeteria kitchens. The historic energy consumption at UDB has been poorly documented. Many buildings lack reliable sub-metered electricity data and no organized record of propane use is readily available.

Energy Efficiency at UDB

To date, only two documented energy efficiency studies have been performed on UDB's main campus. These studies include an assessment of an efficient lighting technology in Edificio tres (performed by Mauricio Gomez), and a study on the quality of energy received in the Engineering Buildings (performed by Federico Machado and Wilfredo Monroy). No comprehensive campus-wide energy efficiency investigation has been completed, nor has the university developed a detailed energy efficiency plan for the entire campus.

The lack of research on campus energy use at UDB reflects a larger need for research and innovation in El Salvador. The Salvadoran Foundation for Economic and Social Development (FUSADES) states that in 2008, El Salvador ranked 127th among 131 countries in quality of research institutions (FUSADES, 2009). In 2010, the

U.S. embassy made an effort to improve El Salvador's scientific research capacity by helping to establish the Center for Renewable Energy Research (CIER) on UDB's main campus. The mission statement of CIER is "to promote research and innovation of technologies related to renewable energy and energy efficiency." CIER has realized few projects hitherto because the center is in its initial stages of operation. An in-depth analysis of the energy use in buildings on the UDB campus can be seen not only as an essential step in mitigating UDB's environmental impact, but also as an important first project for CIER, an opportunity for faculty and students to collaborate on applied research, and ultimately an aid to improving El Salvador's international research ranking. For these goals to be achieved, the mechanisms that govern building energy use in tropical climates must first be understood.

Design Concerns and Strategies for Buildings in Tropical Climates

Infiltration of outside air is a critical cause of energy loss in buildings and merits concerted efforts in energy efficiency studies (Woods and Parekh, 1992). Infiltration is defined as the uncontrolled flow of outdoor air into a building through cracks and other unintentional openings and through the regular use of exterior doors for entrance and egress (ASHRAE, 2005). For air-conditioned buildings in tropical climates, air infiltration represents a major cooling load. At a rate of 0.75 air changes per hour (ACH), the infiltration in a typical residence in the tropics represents 25 to 30% of the air-conditioning (AC) load (Sheinkopf, 1989). The amount of infiltration that takes place in a building is driven by the pressure differential between the inside and outside of the building, as well as by the overall tightness of the building's envelope (i.e. floors, walls, and roof/ceiling). Therefore, it is essential to identify and seal the unnecessary openings in the building in order to reduce energy consumption.

Blower door tests can be used to measure air tightness and identify where air leakage takes place in a building envelope. In fact, virtually all knowledge of the air tightness of buildings comes from blower door technology (Sherman, 2005). A blower door test consists of depressurizing or pressurizing the building with a fan introduced through a door until a predetermined pressure difference between the outside and inside of the building is achieved. The airflow required to maintain the pressure differential is then recorded, normalized, and used to compare against industry benchmarks.

Since 1982, the Florida Solar Energy Center (FSEC) has been conducting research on strategies that can reduce the energy consumption of buildings in hot-humid climates. According to their work, the building envelope is where the most cooling loads occur, and effectively reducing the sensible and latent heat gains through the envelope is an essential step for minimizing AC energy consumption (Chasar, 2004). The positive returns obtained from an energy-efficient envelope design can be seen in the results of a DOE-2 computer-based analysis of ten commercial high-rise buildings in the sub-tropical climate of Hong Kong. The study compared the effectiveness of various cooling strategies including air sealing, insulation, reflection, and shading. The results showed that the cooling energy consumption was as much as 35% lower in buildings that effectively utilized the cooling strategies than in the buildings where such strategies were not incorporated (Chan and Chow, 1998).

A common design strategy for reducing cooling demand in hot-humid climates is the implementation of cool roof surfaces. A cool roof uses high thermal emittance materials that reflect the sun's heat back to the sky. In an FSEC field study of seven identically built Florida (U.S.) homes with different roof constructions, it was found that the homes with reflective roofing benefited from as much as a 39% reduction in cooling demand

(Parker, 2003). The materials used to construct a cool roof do not necessarily need to be complex. In the summer of 1994, FSEC simply whitened the existing roofs of nine Florida homes and found a 19% reduction in AC consumption (Parker, 2003).

An additional component of a cool roof can be a radiant barrier, which is essentially a sheet of reflective aluminum foil that is placed inside the attic space to prevent radiant heat gain. The University of Nevada Last Vegas' Energy Research Center compared the energy consumption of a Las Vegas home with a radiant barrier to a neighboring baseline home. The study concluded that the home with the radiant barrier consumed 4.6% less energy per year than the baseline home; the roof in the radiant barrier home cost 5.7% more to build than the roof of the baseline home and had a 9.5 year payback period (Zhu et al., 2009).

Air Conditioners: Efficiency and Impact

When AC is used in tropical climates, it typically represents the largest single energy expenditure in a building (FSEC, 2007). In studying five air-conditioned buildings on the UDB campus, it was estimated that air conditioning composed 35-65% of each building's total energy consumption. According to energy audit studies of residential homes in Florida (U.S.), the most effective means of decreasing the cooling loads in existing buildings are with retrofits to roofs, windows, and duct systems (Parker and Sherwin, 2001). Due to the prevalent use of AC in hot-humid climates, this project focused primarily on the possible methods for reducing the cooling loads of the buildings on the UDB campus.

The SEER (Seasonal Energy Efficiency Ratio) rating procedure was adopted by the US Department of Energy in 1979 to provide consumers with an indication of air conditioner efficiency. SEER value (e.g. SEER 10 or SEER 13) is defined as the total cooling energy delivered divided by the total electric energy input over a typical cooling season (Btu/W·hr). Higher SEER values indicate greater efficiency levels. In terms of energy consumption, an air conditioning unit with a SEER rating of 13 is 30% more efficient than a unit with a SEER rating of 10.

In January 2006, SEER 13 was established as the minimum allowable efficiency for AC units sold in the US. However, in El Salvador, no standard currently exists that guarantees the efficiency of AC units available on the market. The purchase price of an AC unit with a SEER rating of 10 is significantly less than that of a unit with the same cooling capacity and a SEER rating of 13. For this reason, air conditioners with SEER ratings of 10 or less are commonly installed in newly constructed Salvadoran buildings.

The refrigerants used in AC systems are an environmental concern as they commonly contain ozone-depleting CFCs (chlorofluorocarbons) and HCFCs (hydro chlorofluorocarbons). In 1987, the Montreal Protocol established requirements that began a worldwide phase out of CFCs and HCFCs (EPA, 2010a). Refrigerant-22 (R-22), which I found to be used as the heat exchange fluid in all 45 air conditioners reviewed at UDB, is among the substances to be phased out by 2020.

Additionally, a byproduct of R-22 production is HFC-23, which is a greenhouse gas (GHG) with a global warming potential (GWP) 11,700 times higher than that of CO_2 (EPA, 2011). While existing R-22-based systems can continue to be serviced with R-22 until 2020, the EPA recommends that the R-22 be recycled, reclaimed, or destroyed when the systems are serviced. The phase-out of R-22 will require that UDB convert to Montreal

Protocol compliant systems by 2020, which presents an opportunity for UDB to upgrade to more efficient systems. **Proposed Solution**

The objective of this work was to carry out a practical project that would contribute to El Salvador's nascent energy efficiency developments, as well as improve energy efficiency awareness on the UDB campus. Specifically, I performed a broad scale energy audit of the UDB main campus. My primary methods in achieving this goal were as follows: (1) analyze past UDB energy records and make on-site measurements to identify how energy is used on the main campus, (2) identify three energy-intensive buildings with high potential to reduce energy use, and (3) conduct an in-depth study of those buildings in order to provide energy savings recommendations using the simulation tool eQuest.

Methodology

UDB technicians provided records from the campus electricity meters for 2009 and 2010. These records were corroborated by UDB's utility bills from CAESS (A subsidiary company of the American Energy Services (AES) Corporation) and provided a basis to rank the intensity of energy use in each building. In my study of the UDB campus, I implemented a prioritization strategy that identified the buildings that would benefit most from retrofits. This system involved creating a ranking of Building Energy Usage Intensities (BEUI) in kWh/ft^2/year, and Building Energy Usages (BEU) in MWh/year. This strategy not only helps to determine the buildings that have the highest savings potential, but it also can be used as a tool for future energy efficiency studies on campus. A ranking of campus building energy intensities can serve as a guideline for which buildings should be analyzed next, after more intensive buildings have been audited.

Walkthrough Survey and Detailed Analysis

For the three buildings I identified as most energy intensive, I performed technical energy audits and studied the materials and equipment within each building. I conducted interviews with building occupants and technicians in each building so as to become familiar with the maintenance histories and usage schedules. All data were collected at UDB's main campus in Soyapango over a six-week period from June 6th to July 15th, 2011. The following instruments were used to collect data during the auditing process: a Retrotec R43 blower door to assess the amount of infiltration taking place in the buildings; an Onset HOBO U30 data logger to record weekly temperatures in selected rooms and attic spaces and provide estimates of when cooling equipment is used; a FLIR i5 thermographic camera to measure building envelope surface temperatures and thus estimate the amount of heat transfer taking place across the building envelope, and to also identify the heat leaks that result in excessive loss of conditioned air; an Extech Q527 light meter to measure the intensity of light received in the rooms and to verify if the rooms are over-lit; and a Watts Up? Pro power meter to detect the phantom loads that consume small amounts of electrical current while turned off.

The infiltration data provided by the blower door experiments were recorded in units of cubic feet (ft^3) per minute (cfm). In order to compare the infiltration values to the standards specified by the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) and guidelines found in other building literature, I converted cfm to air changes per hour (ACH) using Equation 1.

$$ACH_{50}=60\left(\frac{cfm_{50}}{V}\right) \quad (1)$$

Where

ACH_{50} = Air changes per hour at 50 Pascals pressure difference

cfm_{50} = Infiltration rate at 50 Pascals pressure difference (cfm)

V = Volume of room (ft^3)

The pressure differential across a building will vary with the weather changes throughout the year. To compensate for the seasonal variation of ACH in the building, I used a method developed by the Lawrence Berkley National Laboratory (LBL) called the LBL infiltration model. The LBL infiltration model is approved by the ASHRAE and is one of the most widely accepted techniques for estimating infiltration rates (Sherman, 1987).

Finally, I developed estimates for the infiltration rates in each room of the building by extrapolating the ACH values that I calculated with the LBL infiltration model. The ACH values were calculated based on the estimated leakage areas (ELA) of the cracks in each room and the total wall area of each room. Using Equation 2, I was able to estimate the ACH for each room that was not tested with a blower door.

$$ACH_E=ACH\,\frac{(ELA_E/A_E)}{(ELA/A)} \quad (2)$$

Where

ACH_E = Estimated ACH in a room with an unknown infiltration rate

ACH = ACH in the blower door tested room, calculated with LBL model

ELA_E = Area of building openings (ft^2)

A_E = Total wall area (ft^2)

ELA = Area of building openings in the blower door tested room (ft^2)

A = Total wall area in the blower door tested room (ft^2)

Due to a lack of available UDB architectural building plans, all structural dimensions of the building zones and ductwork were measured by hand on site. Also, the compositions of building materials were determined via visual inspection and entry into attic spaces. A standard survey procedure was developed to document all building envelope information as required by eQuest parameters. The data collected using the aforementioned instruments as well as the data from the building surveys were used to create eQuest building models.

eQuest Modeling

Computer-based simulation is accepted by many energy efficiency studies as a reliable tool for evaluating building energy use and retrofit possibilities (James, 2000; Al-Homoud, 2001; and Zhu, 2006). While there are many simulation tools available (e.g. EnergyPro and Trace700), I chose eQuest to validate my retrofit recommendations. eQuest is a user interface for the industry standard DOE-2 computer program. I decided to use eQuest because it is a user friendly freeware program that offers a comprehensive set of features: eQuest predicts the hourly energy use and energy cost of a building given user-input information including hourly weather data, building layout, HVAC description, and utility rate structure. With eQuest, a user can determine the combination of building parameters that best improves energy efficiency while maintaining thermal comfort

An essential part of an accurate eQuest model is a weather file that is representative of the annual climate in the building location. The weather file for this study was procured from the United States Department of Energy's Energy Efficiency and Renewable Energy (DOE EERE) website for the location of Ilopango Airport in San Salvador, El Salvador. The Ilopango weather station (latitude 13.41°N and longitude 84.07 °W) is approximately 4.7 km (2.9 miles) away from UDB (latitude 13.42 °N and longitude 84.09 °W) it is assumed that the weather trends of the two locations are similar.

In the model calibration process, I reasonably adjusted uncertain model parameters until the simulated outputs matched the monthly electricity bills within a ±10% margin of error. The standards and guidelines for acceptable tolerances of calibrated models vary from ±5% mean error per month (ASHRAE, 2002) to ±15% mean error per month (DOE, 2000). I chose ±10%, as it is a middle ground between the recommended tolerances.

When calibrating a building model it is essential to make justifiable changes to unknown parameters (i.e. occupancy schedules, set points, and infiltration) while leaving the known parameters (i.e. weather data and equipment ratings) untouched. The occupancy schedules are difficult to predict as the day, time, and size of classes change on a semester-to-semester basis. I calibrated the models primarily with adjustments to the occupancy schedules and some alterations to equipment usage schedules and set points. Figure 1 shows the general logic flow diagram I utilized when calibrating the eQuest models.

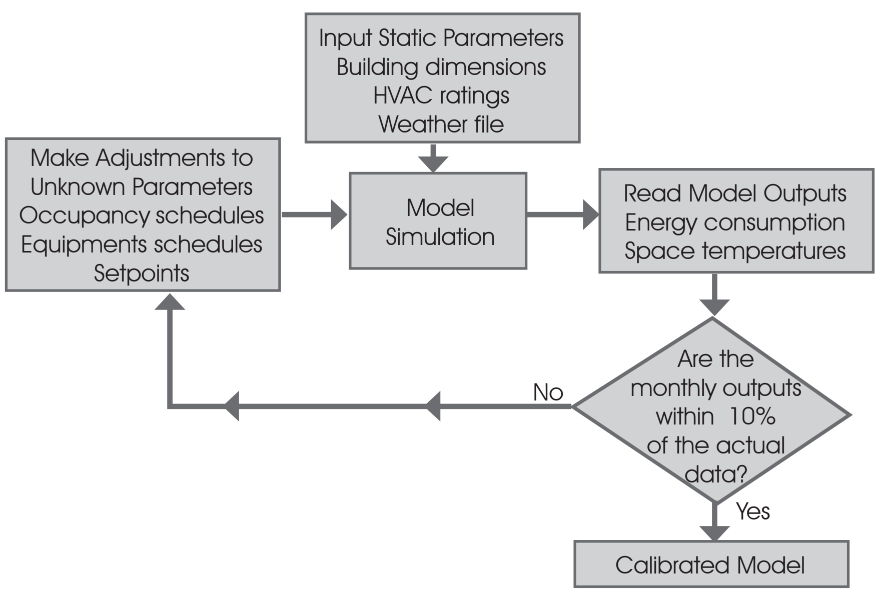

Figure 1: Logic flow chart for calibration process.

Once the models were considered calibrated, I proceeded to test them for retrofit opportunities. The retrofits I tested focused on reducing the building's cooling load with cool roofs and reduced infiltration rates. I also tested the scenario of upgrading the building's cooling equipment to SEER 13 and SEER 16. Last, I modeled various combinations of these retrofits in order to observe how they interact with each other and to identify the highest energy savings options.

Economics

The retrofit possibilities found using eQuest were evaluated for their savings potential and long-term profitability through economic cash-flow analyses over a 20-year period. A discount rate of eight percent was calculated with assistance from the UDB Department of Economics, and was used to represent the time value of money. Price quotes for the materials and installation of each retrofit were procured from various suppliers within the department of San Salvador so as to ensure that the parts and labor are locally available. Using Microsoft Excel, the NPV and payback period of each retrofit were then calculated to determine the most viable alternatives.

Results and Discussion

Both BEU (MWh/year) and BEUI (kWh/year·ft^2) were considered when developing the combined rank in order to avoid investment in energy conservation measures (ECMs) for buildings that have high energy intensities, but small energy uses (Table 1). The combined rank was calculated by simply adding the BEUI and BEU ranks and then sorting those values; priority was given to BEUI over BEU in the case where the combined rank (i.e. BEUI plus BEU) of two respective buildings was equal. The final analysis of campus energy records revealed that the four most energy intensive buildings during 2010-2011 were El Taller Mecánico, La Cafetería, Edificio Cinco, and Edificio Dos (Table 1).

Table 1

Combined rankings of UDB building energy intensities (for the complete list of all 19 UDB buildings see the Supporting Information available online).

Building	BEUI		BEU		Combined Rank
	(kWh/year·ft^2)	Rank	MWh/year	Rank	
El Taller Mecánico	11.5	2	217.7	1	1
La Cafetería	38.6	1	115.7	3	2
Edificio Cinco	6.3	4	123.1	2	3
Edificio Dos	10.4	3	105.4	4	4

Based on energy intensity measured in units of kWh/year·ft^2, *La Cafetería* has the highest energy consumption per ft^2 with 38.6 kWh/year·ft^2. The high BEUI in *La Cafetería* is explained by a large amount of cooking and refrigeration equipment concentrated in a small space. Despite the significant amount of energy used in *La Cafetería*, this project did not consider *La Cafetería* as one of the buildings for in depth audit and study. The decision to exclude *La Cafetería* from detailed analysis was because tenants rent the restaurant spaces in La Cafetería. The property owner-renter relationship commonly creates barriers to implementing ECMs in rented buildings, known as split incentives. Split incentives frequently occur in rented buildings when the decision-maker does not receive many benefits from energy efficiency improvements (Fuller et al., 2009). In the case of implementing ECMs for the UDB Cafeteria, the University would invest in the building upgrades and not receive the reimbursement incentives because the restaurant tenants bear the energy costs. In order to avoid the possible complications with split incentives and to maintain this project's focus on energy efficiency measures for the client, UDB, *Edificio Dos* was chosen as the third building to include for in depth study. In the end, the three buildings I chose for in depth study and investigation of ECMs were El Taller Mecánico, *Edificio Cinco*, and *Edificio Dos.*

Energy Losses and Audit Highlights

Electricity is the only form of energy supplied to each of the three audited buildings. The energy consuming equipment in each building is separated into three categories: (1) air-conditioning (AC), (2) plug loads (i.e. computers, servers, shop equipment etc.), and (3) lighting. All three buildings are two-story multiuse educational facilities that were built in the early 1990s. Because El Taller Mecánico, *Edificio Cinco*, and *Edificio Dos* have similar construction materials and floor plans, the energy losses in all three buildings are due to similar causes. In each of the three buildings the majority of energy wasted is due to three causes: (1) excessive heat gain from the corrugated metal roofs, (2) air infiltration into conditioned spaces, and (3) inefficient cooling equipment.

Thermographic imaging and datalogger readings revealed two principal locations where excessive heat enters the building envelopes: (1) the roof and attic spaces, and (2) the steel doors on the perimeter of the building. The most significant sources of heat gain are through the roof and attic as these spaces are directly exposed to the sun throughout the day (Figure 2). The photos of *El Taller Mecánico* shown in Figure 2 were taken at midday (12:00-12:30 PM CST) on June 23rd, 2011; the outside air temperature during that time was recorded as 25 °C (77 °F). The surface temperature of the roof is approximately 40 °C (104 °F), which is 15 °C (27 °F) hotter than the outside air. The surface temperature of the second floor ceiling is roughly 37 °C (99 °F). The small difference between the surface temperature of the roof and ceiling shows that the majority of the heat absorbed by the aluminum roof is directly transferred into the classrooms and offices. The thermographic images of *Edificio Cinco* and *Edificio Dos* showed similar trends. This large amount of heat transfer demonstrates the need for implementing either a heat barrier or improved ventilation within the attic spaces of all three buildings.

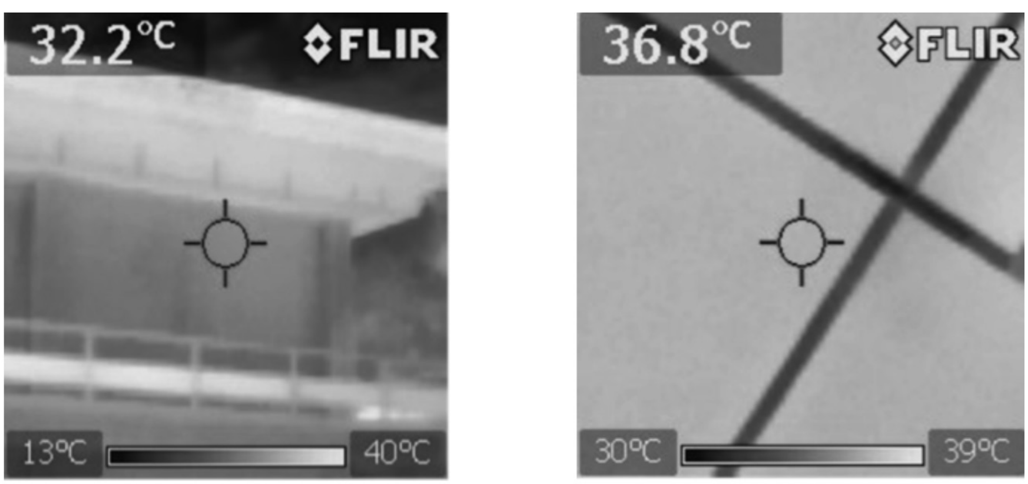

Figure 2: Thermographic images displaying the high surface temperatures (left) and the second floor ceiling (right) of El Taller Mecánico. The Outside air temperature was recorded as 25 °C (77 °F).

A datalogger with a temperature sensor was placed in the attic for a one-week period (June 18th to 24th, 2011) to measure the heat intensity in the space over time. The datalogger was not placed in *Edificio Cinco* because the majority of the cooling demand takes place on the first floor where there is sufficient shading from surrounding trees and buildings. Because of this setting, heat transfer from the roof is not as much an issue in *Edificio Cinco* as in *El Taller Mecánico* and *Edificio Dos.* As shown in Table 2, during the hours of 9AM-5PM, the data recorded in *El Taller Mecánico* and *Edificio Dos* showed average temperatures of 36 °C (96 °F) and 44 °C (112 °F), respectively; the peak attic temperatures were 45 °C (113 °F) and 52 °C (125 °F), respectively. The average high outside temperature during the week the datalogger was placed in *El Taller Mecánico* was 25 °C (77 °F), and during the week when the device was placed in *Edificio Dos* the average high outside temperature was 34 °C (93 °F). These measurements imply that on average, the attic spaces are significantly hotter than the outside air. The consistent high temperatures within the attic undoubtedly provoke excessive energy consumption by forcing the AC units to run for longer time periods in order to remove warm air from the building.

Table 2

Attic space temperature profiles for the hours of 9AM-5PM recorded over a one-week period.

Building	Average High Outside Temperature	Average Attic Temperature	Peak Attic Temperature
El Taller	25 °C (77 °F)	36 °C (96 °F)	45 °C (113 °F)
Edificio Dos	34 °C (93 °F)	44 °C (112 °F)	52 °C (125 °F)
Edificio Cinco	NA	NA	NA

The blower door tests revealed that there are two main sources of outside infiltration into the conditioned rooms of the buildings: (1) the crack spaces under perimeter doors, and (2) the louvered *(Aire Sol)* windows. There are also a few leaks and cracks in some ceiling panels, which likely cause additional infiltration of unconditioned air. Unfortunately, these ceiling leaks could not be measured empirically with blower door tests, as the ceiling is not sufficiently strong for an individual to walk on top and cover the leak. Additional leaks exist underneath interior doors, but are not considered significant as they permit air exchange between conditioned zones.

One blower door test was performed in *El Taller Mecánico* to determine the amount of air infiltration through the crack spaces below the perimeter doors. A second blower door test was performed in *Edificio Cinco* to calculate the amount of infiltration that results from the louvered (*Aire Sol*) windows. Table 3 illustrates the results from both experiments with the fenestrations uncovered (i.e. under normal conditions) and Table 4 shows the results with the fenestrations covered (i.e. under improved energy-efficient conditions).

Table 3

Blower door test results with fenestrations uncovered.

Test Location	Fenestration Tested	Volume (ft^3)	Cfm_{50}	ACH_{50}	Seasonal ACH
El Taller Mecánico (Room 6.22A/B)	Perimeter Cracks	7,225	8,800	73.1	4.1
Edificio Cinco (Room 5.10)	Louvered Windows	2,977	1,100	22.2	1.2

Building tightness factors (i.e. leaky or tight) and corresponding levels of ACH_{50} vary by climate, building size, and building age. However, generally speaking, houses with less than 5-6 ACH_{50} are considered tight, and those over 20 ACH_{50} are leaky (Keefe, 2010). Under these guidelines, both of the test rooms are leaky and in need of air sealing.

Table 4

Blower door test results with fenestrations covered.

Test Location	Fenestration Tested	Cfm_{50}	ACH_{50}	Seasonal ACH
El Taller Mecánico (Room 6.22A/B)	Perimeter Cracks	6,400	53.1	3.0
Edificio Cinco (Room 5.10)	Louvered Windows	100	2.0	0.1

The ACH_{50} and seasonal ACH in the test rooms decrease when the fenestrations are covered (Table 4). The seasonal ACHs in Table 4 are considered the potential infiltration levels if the fenestrations were sealed. In the case of Room 5.10, the infiltration is reduced to 0.1 ACH when the windows are sealed. According to ASHRAE standard 62, buildings without forced air ventilation require 0.35 ACH or higher in order to prevent what is known as "sick building syndrome" (SBS), where building occupants suffer from poor indoor air quality and inadequate ventilation (EPA, 2010b). Therefore, the building envelope should not be made overly tight when sealing fenestrations.

The blower door data were extrapolated to the remainder of the rooms in *El Taller Mecánico, Edificio Cinco,* and *Edificio Dos* based on the estimated leakage areas (ELA) in each conditioned room (Equation 2). A data spreadsheet containing projections of the present infiltration levels in each building was developed using Equation 2. These data were ultimately used as the infiltration parameters for the baseline eQuest model of each building (the full spreadsheet can be found within the Supporting Information online).

Upon obtaining the characteristics for heat transfer and air infiltration, the buildings' cooling equipment systems were surveyed. This part of the study revealed that all 41 AC units that serve *El Taller Mecánico, Edificio Cinco,* and *Edificio Dos* are rated at SEER 10.8 or less; these AC units are considered very inefficient by today's standards. The American Council for an Energy Efficient Economy (ACEEE) recommends consumers in all climates purchase new cooling equipment of SEER 14.5 or higher (ACEEE, 2011). Unfortunately in El Salvador, SEER 13 is the most efficient AC unit widely available on the market. While it is possible to purchase cooling equipment with a SEER of 16, the equipment is typically only available in small cooling capacities (i.e. one or two tons). The efficiency benefits of upgrading to SEER 13 and SEER 16 is discussed in following paragraphs.
An additional issue with the AC equipment installed at UDB is that many of the units are exposed to direct sunlight throughout the entire day. This setup decreases both the efficiency and the life expectancy of the AC units. The estimated energy savings achieved from AC shading vary from 2-10%, depending on the shading structure's ability to cool the air that comes in contact with the AC condenser (Parker et al., 1996). While it is important that the AC unit be installed in a shady area, it is equally important that the chosen location does not impede the natural airflow to the AC condenser.

eQuest Model Calibration and Results

The data collected during the audits (i.e. building materials, equipment specifications, readings from auditing instruments/tools, and information gathered from building occupants and technicians) were ultimately used to create eQuest models of El Taller Mecánico, Edificio Cinco, and Edificio Dos. Several calibration iterations were carried out for each model based on changes to occupancy schedules, cooling setpoints, and infiltration rates for the zones where sufficient data were not available. Upon calibration, the monthly energy outputs of each baseline model are within a ±10% margin of error when compared to the actual utility bills.

Three potential retrofits were analyzed for all three buildings: (1) implementation of cool roofs, (2) reduction of outside air infiltration, and (3) an upgrade to SEER 13 cooling equipment. Additionally, an upgrade to SEER 16 cooling equipment was modeled for *El Taller Mecánico* and *Edificio Cinco*. The SEER 16 upgrade was not modeled for *Edificio Dos* and instead a 15-ton central cooling system was modeled (Table 5). This alternative retrofit was chosen for *Edificio Dos* because *Edificio Dos* has a distinction among the buildings on the UDB campus in that it has an extensive duct network that runs through four conditioned zones in the building;. The duct network is currently connected to six split AC systems, but the network could possibly be used to distribute air from a centralized cooling system instead. This modeled retrofit accounted for seven additional split AC systems to service the zones that are not connected to the duct network.

Table 5

Summary of retrofit alternatives for all three eQuest modeled buildings.

Building	Alternative	Consumption (MWh/year)	Savings (MWh/year)	Reduction in Total Energy Consumption	GHG Abatement (tCO_2e/year)
El Taller Mecánico	Baseline	213.5	-	-	-
	Less Infiltration	211.4	2.1	1.0%	1.2
	Cool Roof	207.9	5.6	2.6%	3.2
	SEER 13	184.5	29.0	13.6%	17.2
	SEER 16	174.3	39.2	18.4%	23.2
Edificio Cinco	Baseline	121.9	-	-	-
	Cool Roof	118.6	3.3	2.7%	2.0
	Less Infiltration	118.5	3.4	2.8%	2.0
	SEER 13	99.5	22.4	18.4%	13.3
	SEER 16	81.9	40.0	32.8%	23.7
Edificio Dos	Baseline	108.7	-	-	-
	Cool Roof	107.6	1.1	1.0%	0.7
	Less Infiltration	104.7	4.0	3.7%	2.4
	SEER 13	95.5	13.2	12.1%	7.8
	15-ton Central Cooling System	94.5	14.2	13.0%	8.4

The results for all three buildings show that the most energy can be saved with upgrades to new cooling equipment (i.e. SEER 13, SEER 16, or the central cooling system). The cool roof and infiltration-reducing retrofits are less costly investments and are also viable energy saving options.

To alleviate the heat gain through the roof and attic in El Taller Mecánico, *Edificio Cinco*, and *Edificio Dos* the eQuest models were simulated with added cool roof constructions, which are inclusive of the radiant barrier. The cool roof retrofits are estimated to reduce 31 MBtu/month of heat gain in both *El Taller Mecánico* and *Edificio Cinco* and reduce 17 MBtu/month in *Edificio Dos*. These decreases in heat gain through the roof will not only reduce electric energy use, but will also provide cooler, more comfortable conditions for the building occupants.

The results from the blower door experiments show that the rooms in *El Taller Mecánico, Edificio Cinco,* and *Edificio Dos* are highly permeable and are in need of air sealing. To model this retrofit the eQuest infiltration parameters were reduced to 0.5 ACH in all conditioned rooms of the buildings. It is assumed that 0.5 ACH can be achieved by installing weather stripping below perimeter doors, fixing broken ceiling panels, and replacing the louvered windows in conditioned rooms with sealed windows. eQuest can generate a report that describes a building's monthly cooling load due to infiltration. According to this report, a reduced infiltration rate will decrease the cooling load by 27 MBtu/month in *El Taller Mecánico*, 16 MBtu/month in *Edificio Cinco,* and 58 MBtu/month in *Edificio Dos*. Similar to the aforementioned cooling effect of the cool roof, these reductions in convective heat gain will save energy and provide a more confortable atmosphere for the building occupants.

Some of the AC units installed at UDB are more than 15 years old, and all of the AC units are very inefficient by today's standards. A cooling equipment retrofit was simulated in eQuest by increasing the condenser coefficient of performance (COP) of all AC units. This retrofit assumes that all the upgraded AC units will have the same cooling capacities (i.e. 44 tons in El Taller, 63 tons in *Edificio Cinco,* and 46 tons in *Edificio Dos*) and usage schedules as the previous AC units. It should be noted that there may be obstacles to procuring SEER 16 cooling equipment in El Salvador. Many of the AC suppliers I spoke with in El Salvador noted that the current demand for SEER 16 equipment is small and therefore the availability of SEER 16 is limited.

Three alternatives for improved cooling equipment were modeled, one for SEER 13, SEER 16, and a 15-ton centralized chiller system rated at SEER 13. The new cooling systems would utilize refrigerant 410A (R-410A) instead of R-22, which is currently used in all of UDB's AC systems. According to the EPA, R-410A is an acceptable substitute for R-22 as it does not contribute to depletion of the ozone layer, but like R-22, does contribute to global warming (EPA, 2010a). The 100-year GWPs of R-22 and R-410a are 1,810 CO_2e and 2,090 CO_2e, respectively (IPCC, 2007). Essentially, if the R-410A were to leak or be released into the atmosphere, it would act as a GHG in a similar way as the existing R-22. However, since the R-410A will be used in more efficient cooling equipment (i.e. higher SEER) it will reduce UDB's GHG emissions due to a reduction in electric power consumption.

Economics

Combinations of the retrofits presented in Table 5 were tested to observe how the retrofits interact with each other. Analyses for a total of 36 retrofit alternatives were performed for the three audited buildings. The

Net Present Value (NPV) and payback period are used to compare the different alternatives. The retrofits recommended have a range of initial investments so as to provide UDB with various options and levels of financial commitment. In all options, the NPV is a factor of the initial investment, where a higher initial investment equals a higher NPV.

From the analysis, it was found that the most lucrative retrofits are reducing infiltration rates in *Edificio Dos,* implementation of a cool roof for *El Taller Mecánico,* and upgrading to SEER 13 cooling equipment in *El Taller Mecánico* (Table 6). These retrofits were selected based on their quick payback periods and their favorable NPVs. The retrofits shown in Table 6 are not the only options that yield positive returns. In fact, 18 of 36 simulated retrofits are projected to pay for themselves within a 20-year period. The 15 remaining retrofits not shown here could potentially be funded by the positive returns received by the retrofits presented in Table 6 after having reached their full payback period.

Table 6

Overview of the most economically promising retrofits for UDB.

Retrofit and Building	Initial Investment	Energy Savings (kWh/yr)	First Year Savings ($)	NPV ($)	Payback (years)	GHG abatement (tCO_2e/yr)
Less Infiltration (*Edificio Dos*)	$3,452	4,030	$605	$3,954	7.1	2.4
Cool Roof (El Taller Mecánico)	$4,717	5,540	$831	$4,639	7.7	3.3
SEER 13 Upgrade (*El Taller Mecánico*)	$24,505	28,950	$4,343	$20,680	7.0	17.2

It was found that reducing the infiltration rates within *El Taller Mecánico and Edificio Cinco* will produce energy savings but not sufficient to justify the costs to replace the 1,600 ft^2 and 2,300 ft^2 of louvered (*Aire Sol*) windows, respectively.

The cool roof retrofit saves the most energy when implemented in *El Taller Mecánico* than in *Edificio Cinco* or *Edificio Dos.* This is due to the fact that all 13 AC units in *El Taller Mecánico* service the second floor as opposed to *Edificio Cinco* and *Edificio Dos* that both have several AC units that service the first floor where there is substantial shading from neighboring buildings and vegetation.

SEER 13 upgrades in all three buildings earn positive returns. However, the investment is best made in *El Taller Mecánico.* This finding is due to the simple fact that the *El Taller Mecánico* runs a larger percentage of its AC fleet consistently throughout the day than compared to *Edificio Cinco* or *Edificio Dos.*

Conclusions

The most energy intensive buildings on the UDB campus are El Taller Mecánico, *Edificio Cinco,* and *La Cafetería.* However, due to the split incentives between UDB and the restaurant renters in *La Cafetería*, the building was not selected for in depth analysis. In place of the Cafeteria, the fourth most intensive building (*Edificio Dos*) was selected for detailed audit and analysis.

The walkthrough audits showed that air conditioning (AC) is the biggest electrical load in all three of the audited buildings. To minimize AC energy consumption in these buildings, the eQuest modeled retrofits focused on preservation of conditioned air within the building, reduction of radiant heat gain, and installation of more energy efficient equipment. UDB's two most practical design strategies for preserving conditioned air are: (1) the installation of cool roofs and (2) reducing the infiltration rates within conditioned rooms. Through eQuest modeling, it was found that these strategies not only reduce AC energy use, but also provide a cooler, more comfortable atmosphere for building occupants.

In all three of the audited buildings, it was found that the most energy is wasted due to the following three causes: (1) intense heat gain from the corrugated metal roofs, (2) excessive infiltration from louvered windows and cracks below doors, (3) and outdated AC equipment. Various retrofit scenarios were modeled in eQuest to assess their energy savings potential and were accompanied by economic analyses. Because similar building constructions are found throughout Central America, it is likely that the retrofits recommended in this article can be applied to buildings within the region.

Multiple ECMs were analyzed for each building so as to accommodate whatever budget UDB has available for campus energy efficiency investments. The retrofits can be implemented in steps, starting with the retrofits that have lower initial investments and faster payback periods. With this strategy the savings generated from the cheaper retrofits can be used to facilitate the more expensive ones.

The economic analysis showed that upgrades to SEER 16 cooling equipment save more energy than SEER 13 and, in most cases, have a higher NPV. However, the upfront cost and time to payback of the SEER 16 retrofits are substantially higher than the SEER 13 retrofits, and as such the SEER 13 retrofits are preferred. Furthermore, there is limited availability of SEER 16 equipment in El Salvador.

The economic evaluation of the 36 retrofit scenarios for the three audited buildings showed that the three best options in increasing order of NPV are: (1) reducing infiltration rates in *Edificio Dos*, (2) implementation of a cool roof for *El Taller Mecánico*, and (3) upgrading to SEER 13 cooling equipment in *El Taller Mecánico.* These retrofits are expected to save 4.0 MWh/year (1), 5.5 MWh/year (2), and 28.9 MWh/year (3) respectively and the discounted payback periods are forecasted at 7.1 years (1), 7.7 years (2), and 7.0 years (3), respectively. A complete table of the energy savings potential and economic figures for all 36 retrofit scenarios, as well as other supporting information from this study can be found at http://humboldt-dspace.calstate.edu/handle/2148/982.

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