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Keywords: measurement and verification, building performance simulation, energy audit, LEED, green retrofit, existing building

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This study investigated the process of existing building green retrofits through examining a Leadership in Energy and Environmental Design for Existing Building: Operations and Maintenance (LEED EBOM) Gold project. The project demonstrated a standard green retrofit process for existing buildings, which includes energy auditing, building performance simulation, and measurement and verification. In this project, four energy conservation measures were applied to improve energy performance: light-emitting diode (LED) lighting, window films, green roofs, and chilled water plant upgrading and optimization. The expected energy saving was 30% after the retrofit; while the actual energy saving was 16%. The error of building performance simulation was one of uncertainties in this retrofit project. Occupancy conditions might be the main reason for this uncertainty. Strengths, weaknesses, opportunities and threats were identified and discussed for the green retrofit. The research results could be used to optimize the existing building retrofit process for better energy performance.

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Case Report

Strengths and Weaknesses of Existing Building Green Retrofits: Case Study of a LEED EBOM Gold Project

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Keywords: existing building; green retrofit; LEED; energy audit; building performance simulation; measurement and verification

1. Introduction

Existing buildings, especially non-residential buildings, contribute to a significant portion of greenhouse gas emissions [1]. There is an urgent call for reducing the environmental impact of existing buildings via retrofitting [2]. It is well known that the majority of existing buildings last for 50–100 years [3] and that retrofitting existing buildings is more resource-efficient and sustainable than building new green constructions [4,5]. Through modifications, demolition and rebuilding could be avoided; consequently, less construction wastes are generated and less material resources are required [6].

Retrofitting was defined as some modification or conversion instead of a complete replacement of an existing process, facility or structure [7]. It might involve additions, deletions, rearrangements or replacements of one or more parts of the facility [8]. The retrofitting of existing buildings usually includes enhancing efficacy of the air-conditioning system [9–11], upgrading the lighting system [12,13], implementing lighting controls [14,15], and improving thermal insulation of building envelopes [16] and roof systems [17]. Studies showed that these retrofits could significantly reduce energy consumptions of existing buildings and energy costs while enhance occupants' comfort [18].

Typically, a retrofit project involves three key steps: energy auditing, building simulation and measurement and verification (M & V). An energy audit is the process of inspecting, surveying and analyzing the current situation of energy uses in a building; it is the first step to identify opportunities to reduce energy uses [19]. It plays a key role in understanding existing building energy uses and proposing cost-effective Energy Conservation Measures (ECMs). ASHRAE [20] recommended three levels of energy auditing: Level 1: "walk-through" which includes a review of utility bills or other operating data and a walk-through of the facility to identify issues related to energy waste or inefficiency; Level 2: "energy survey and analysis" that adds detailed energy calculations and financial analyses of proposed ECMs; and Level 3: "detailed analysis of capital intensive modifications" which focuses on an engineering analysis of the potential capital-intensive projects identified in Level 2.

Identifying ECMs and evaluating their effectiveness are most important in an energy audit project [21]. Krarti [22] categorized common ECMs on the following building elements: building envelopes, electrical systems, HVAC systems, compressed air systems, energy management controls, indoor water management and new technologies. To understand their effectiveness of improving energy performance, building performance simulation is used as an instrument in the retrofitting process [23]. The building simulation can help to predict the peak values and load profiles of heating/cooling loads of buildings which could be used as the basis for the upgrading HVAC equipment, systems, and plants [24]. Furthermore, innovative strategies for energy saving such as reflective roof, daylighting, free-cooling, solar hot-water heating, heat recovery, and thermal storage can be evaluated before implementation [25]. Last but not least, after the retrofit, measurement and verification should take place to verify the effectiveness of the retrofit.

At the same time, the building retrofit or refurbishment faces many challenges and uncertainties, such as climate change, services changes, users' behavioral changes and technological changes, all of which directly affected the selection of retrofit techniques and hence the success of a retrofit project [26,27]. Other challenges might include financial barriers and long payback periods [28]. One important strategy to reduce the retrofit risks and uncertainties is adopting green building certification [7,29,30]. In recent years, LEED has been emerging as a popular rating system to evaluate the environmental performance of a building and encourage market transformation towards sustainable design [31]. LEED has established a number of programs aiming for different real estate markets, one of which is dedicated to existing building retrofits: LEED EBOM. LEED EBOM defines the green retrofit as "an upgrade at an existing building to improve energy and environmental performance, reduce water use, improve comfort and quality of space in terms of natural lighting, air quality and noise" [32]. Similar to other green rating tools, LEED EBOM covers six aspects (Figure 1). Among all aspects, Energy and Atmosphere is the most important and accounts for the largest portion of points. Table 1 shows the specific credits and points involved in Energy and Atmosphere. More details of this program could be found in the reference guide of LEED EBOM [33].

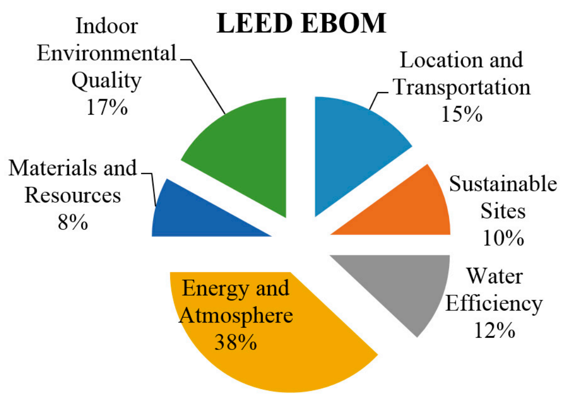

Figure 1. LEED EBOM aspects (Data Source: USGBC 2014).

Table 1. Credits and Points of Energy and Atmosphere in LEED EBOM (Data Source: USGBC 2014).

	Energy and Atmosphere	Point (s)
Prerequisite	Energy Efficiency Best Management Practices	Required
Prerequisite	Minimum Energy Performance	Required
Prerequisite	Building-Level Energy Metering	Required
Prerequisite	Fundamental Refrigerant Management	Required
Credit	Existing Building Commissioning—Analysis	2
Credit	Existing Building Commissioning—Implementation	2
Credit	Ongoing Commissioning	3
Credit	Optimize Energy Performance	20
Credit	Advanced Energy Metering	2
Credit	Demand Response	3
Credit	Renewable Energy and Carbon Offsets	5
Credit	Enhanced Refrigerant Management	1
	Total	38

A number of studies have been conducted to verify the impact of LEED certification on building energy and environmental performance [34–36]. These studies showed the benefits of an existing building retrofit and green building certification to building owners, tenants and occupants [37]. The present study, investigating into a LEED EBOM certified project, intends to understand the methodology and process of an existing building green retrofit project. The present study also aims to disclose the strengths and weakness of each retrofitting step and to optimize the retrofit process to increase the effectiveness of retrofitting. Although many studies can be found in the subject of energy retrofit, they mainly used building simulation to verify the ECMs and their related outcomes theoretically. This study, using a real project and a longitudinal investigation through the whole retrofit process, provides first-hand empirical data and facts on each stage of retrofitting. Furthermore, based on the real case, this paper summarizes the methodological strengths and weaknesses of the green retrofit process.

2. Methodology: Case Study

To meet the research objective, this paper investigated a LEED EBOM project which had gone through a rigorous green retrofit process. The data for this paper were collected from the whole retrofitting process. The building selected for this study is the Chow Yei Ching (CYC) Building (Figure 2) which belongs to the University of Hong Kong. The University of Hong Kong sets sustainability goals, one of which is to significantly reduce the energy consumption of existing buildings. The CYC building was selected for an energy efficient retrofit to achieve LEED EBOM Gold certification (Table 2). The CYC building is located on the main campus of the University of Hong Kong. It was built in 1993 and now it is a multi-purpose academic building which comprises offices, lecture rooms and different types of laboratories. It has a total of 13 floors from LG4/F to its highest 8/F. The GFA is around 13,168 m^2. Hong Kong is located at latitude 22.2783° N and longitude 114.1747° E. Hong Kong's climate is sub-tropical. August and September are the hottest months with high humidity, which are the highest energy consumption period due to the need of cooling. The major energy consumers of this building are the air conditioning system, lighting system and office equipment. To conduct the retrofit project, the university employed an energy service company to manage the technical and funding issues. Other parties such as Estate Office, electrical/electronic technicians, and LEED consultants were involved to follow the energy measurements, to supervise the implementation and to ensure the achievement of LEED certification. The CYC project went through a standard retrofit process. A walk-through assessment and an energy survey were conducted in the year of 2011 before the retrofit was implemented. Based on the energy audit, several ECMs were recommended. Building performance simulation was conducted to look at detailed cost-effectiveness of these ECMs. The retrofit period was March 2012 to July 2013. The operation period after the retrofit was August 2013 to August 2014, during which the measurement and verification was conducted.

Figure 2. The CYC building: north façades (**left**) and south façades (**right**) (Photo by authors).

Table 2. LEED facts for the CYC project (Source: https://www.usgbc.org/projects/hku-chow-yei-ching-building).

LEED O+M: Existing Buildings (v2009); Certification Awarded: Jun 2015		
Categories	**Possible Credits**	**Achieved Credits**
Sustainable Sites	26	17
Water efficiency	14	13
Energy & Atmosphere	35	19
Material & Resources	10	5
Indoor Environmental Quality	15	6
Innovation	6	5
Regional Priority Credits	4	4
Integrative Process Credits	1	0
In total	106	69 (Gold)

3. Results

3.1. Energy Audit

The energy audit was conducted to find the current condition of the CYC building. The content of the energy audit is shown in Table 3. Different methods, such as "walk through", "on-site measurement" and "electricity bill reading", were used in the energy auditing process, based on which ECMs were recommended for the retrofit.

Table 3. The content of the energy audit.

Content		**Details**
Building Envelope	Exterior walls Windows Doors Roof	geometrical configuration, construction materials, u value, window/wall ratio

Table 3. *Cont.*

Content		Details
System/Equipment	Chiller Plant	type, capacity
	AHU Ventilation Fans FCU Lighting System	specifications, number, schedule
	Lift System	types, speed, number, duty
	Power Quality System	power factor
Energy Use	Electricity Bill	monthly electricity bills
Occupancy Pattern	Operating Hours Occupancy Number Occupancy Schedule	day time and after–hours weekdays and weekends
Indoor Environment Quality	Temperature, Relative Humidity, Ventilation rate, CO_2	occupied areas

The energy auditing started from the building envelope. The exterior walls consisted of 150 mm thick concrete blocks with face brick exteriors. The windows consisted of a combination of single pane glass with aluminum frame. Large window areas were found facing north (440 m^2) and south (388 m^2). The roof construction consisted of 150 mm thick concrete blocks. The total surface area of roof floor was around 1013 m^2.

The major part of the energy audit was focused on mechanical and electrical systems, such as chiller plant, AHU, VF, FCU, lighting and lifts. A chiller plant located at the roof floor provided the cooling of the whole building. The chiller plant consisted of four air-cooled 180 tons chillers, four primary chilled water pumps and three secondary chilled water pumps. The chiller plant was installed with Honeywell building management system. It was found that some of the sensors such as temperature sensors and flow sensors were mal-functional. The chiller plant could not be operated fully automatically. Due to the operation requirements in laboratories and facilities such as computer servers, the plant was in 24 h operation to maintain suitable conditions.

Various types of lighting fixtures were installed at CYC. Most of them were T8 tubes with electronic ballasts. All lighting fixtures were controlled by conventional timers according to the pre-set time schedule. A total of four lifts are installed in the CYC building. One of them is a service lift. Power factor is one of the major concerns for good power quality within a building. It affects the demand side management and also the electricity costs. During the site visit, the power quality was in good condition with the power factor at 0.98.

The building was occupied by around 700 staff from 8:30 a.m. to 7:00 p.m. Monday to Friday and 8:30 a.m. to 12:30 p.m. on Saturday. To better understand the IEQ in the CYC Building, the research conducted on-site measurements before the retrofit. The measurement was conducted at different locations covering individual offices, open-plan offices, laboratories, corridors, toilets, and entrances/exits during occupied conditions. For small spaces such as individual offices, the measurement took place nearby the seat positions of the occupants; while for large spaces such as open-plan offices and laboratories, the measurement took place at several different seat positions to cover window, middle and isle seats. In total, 47 points were measured. The measurement was conducted during office hours. Figure 3 shows the measurement results. Compared to the temperature set point which was 24 °C, many spaces were warmer than expected, especially corridors, entrances/exists and some offices on the top floors, while some individual offices and laboratories were colder. The occupancy and floor conditions were the main reason for the temperature variation. Higher occupancy load in open-plan offices and laboratories resulted in higher heat dissipations both from human bodies and equipment. Higher floors, especially the top floors, too, had more heat gains from the roofs. The private offices and lower floors, on the contrary, had less heat gains and consequently lower temperature. The relative humidity and carbon dioxide concentration had similar trend.

The retrofitting project was expected to be conducted during the year 2010 to 2011, so energy consumption data from the closest year 2009 were analyzed. Figure 3 shows the electricity data for the CYC building in the year of 2009. The total electricity use was 3,742,860 kWh at a total cost of HK$4,695,048 (with the charge at HK$1.254 per kWh). Table 4 breaks down the energy use. The air-conditioning system took up more than 40% of the building energy use. Lighting accounted for 16% and lifts consumed 10%.

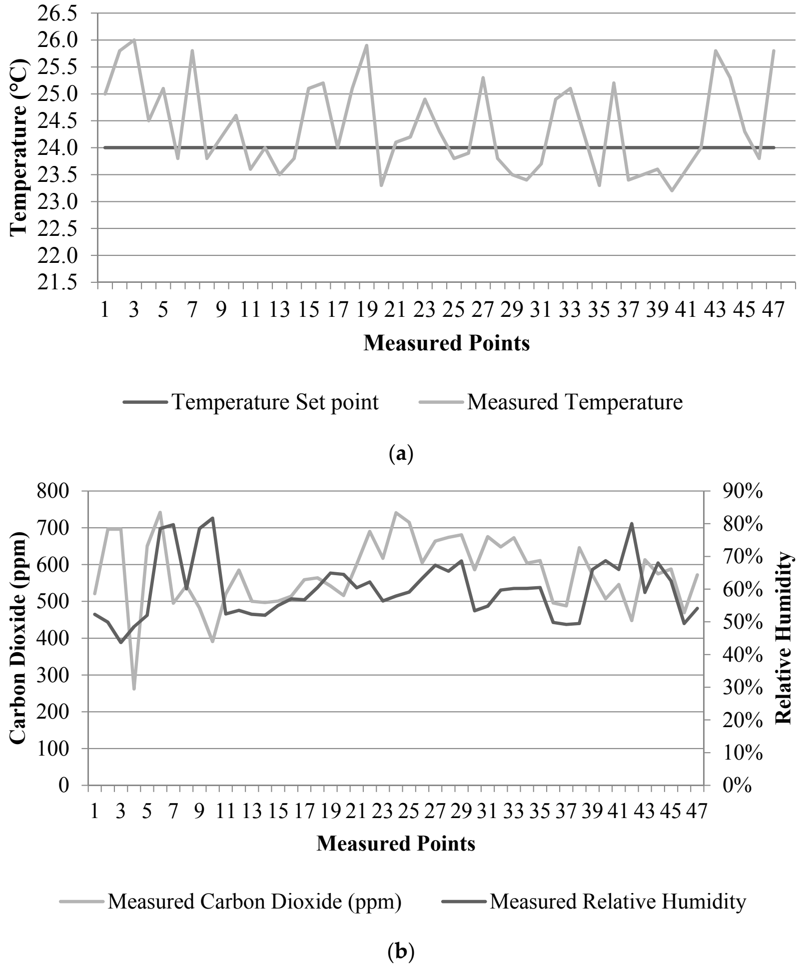

Figure 3. Indoor environment quality of the CYC building. (**a**) Temperature; (**b**) Carbon Dioxide and Relative Humidity.

Table 4. Energy use breakdown.

Equipment	Annual Consumption (kWh)	Percentage
Chiller Plant	918,793	24%
AHU	152,802	4%
PAU	67,663	2%
VF	183,141	5%
FCU	146,189	4%
Split Unit	59,227	2%
Lighting System	604,291	16%
Lift System	374,296	10%
Others (lab facilities)	1,236,458	33%
Total	3,742,860	100%

Based on the energy auditing and diagnostics of the CYC building, four ECMs were selected to reduce its energy consumption.

- Lighting Retrofit: Currently in the CYC Building, 90% of the general lighting fixtures used fluorescent tubes. LED, a semiconductor light source, is considered as the ultimate general lighting solution due to a low power consumption, high efficiency and long life span.
- Green Roofs: The poor thermal insulation of the roofs which was flat with 150 mm concrete blocks caused solar heat gains in offices at top floors. It was suggested to build a green roof at the flat roof area.
- Window Film Coating: The SHGC for windows was approximately 0.82. The large value of coefficient resulted in large amount of heat transfer. It was proposed to coat windows with 3M^{TM} Night Vision window films that allow 35% daylight in (3M NV 35). The total area of the window film coating was approximately 843 m^2.
- Updating Chiller Plant and Building Management System Installation: The existing chiller plant was low efficiency with COP at 2.6 (0.7 kW/ton); for a well-designed all variable speed plant, the COP should be above 5.0 (i.e., 1.35 kW/ton). A new plant was to be built the replace the old one.

3.2. Building Performance Simulation

In order to determine the benefits of proposed ECMs to the CYC building, building energy simulation was conducted using EnergyPlus. In the project, the latest Version of Energy Plus v8.1/8.0 was employed. This version was authorized by U.S. Department of Energy and Building Technologies Program. In this research, the building information model was created in DesignBuilder and then exported into EnergyPlus for energy simulation. The simulation process is shown in Figure 4.

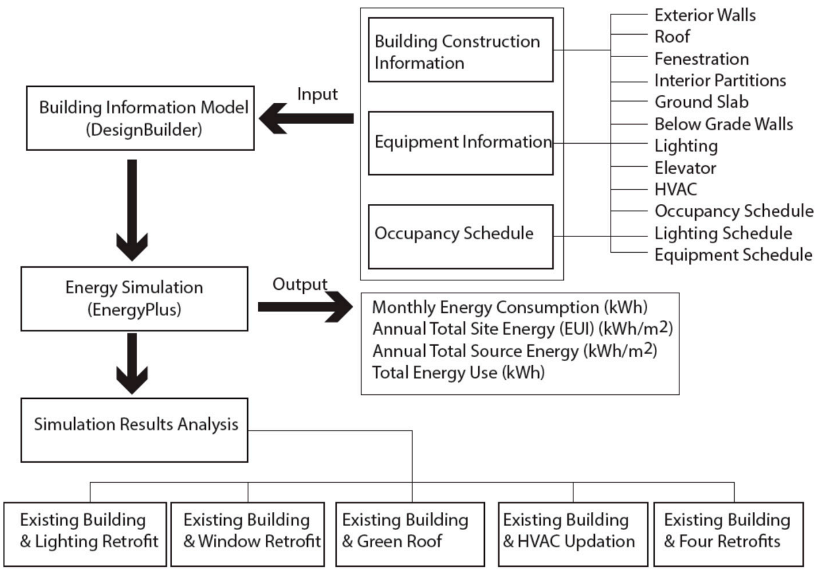

Figure 4. Simulation process.

In the simulation model, the thermal zone was defined according to the partitions of the space and the function of the space. The major thermal zones in each floor of CYC were identified as office, laboratory, service room, bathroom, lobby and corridor, AHU and lecture room. For each thermal zone of the floor, the total number of lighting fixtures and occupants were counted based on the energy audit result. The power densities of equipment and lighting were calculated according to the ASHRAE Standard. Table 5 summarizes the building information settings using ASHRAE 90.1 as a baseline [38]. Other building information such as occupant schedule, lighting schedule and equipment schedule were collected through the energy audit process as discussed before.

Table 5. CYC building construction and services information.

Item	Existing Building Description	Base Line (ASHRAE Standards 90.1-2007)
	External Walls	
Type	Solid Concrete Brick Wall	Steel-Framed
U-Value (W/m^2·K)	0.600	0.705
	Roof	
Type	150 mm Concrete Deck Flat Roof	Insulation Entirely above Deck
U-Value (W/m^2·K)	0.450	0.273
	Fenestration	
Glazing Type	6mm Single Glazing, clear glass, no shading, with Aluminum window frame	Glazing with metal framing
WWR	25.6%	0–40%
U-Value (W/m^2·K)	6.148	4.26
SHGC	0.82	0.25
	Interior Partitions	
Type	Slab on grade (unheated)	Slab on grade(unheated)
F-factor (W/m^2·K)	1.360	1.264
	LPD (W/m^2)	
Lecture/Meeting/Library room	12	14
Office	10	12
Laboratory	14	15
Service/Rest Room	8	10
Corridor/Staircase	4	5
Lobby	8	14
	Temperature Set Point	
Cooling Set Point (°C)	24	24
Cooling Set Back (°C)	28	37
	Occupancy Density (m^2/person)	
Meeting/Library Room	4	2.8
Lecture Room	1.5	1.4
Office	8	11.1
Laboratory	5	9.3

Validation was conducted to verify the simulation by comparing the simulation results with the actual energy use in 2009. Validation is an essential task to ensure that building systems are properly modeled and integrated for the purpose of simulating the building energy consumption [39]. Table 6 shows the simulated energy use data compared with the actual data of 2009.

Table 6. Simulated Energy Consumption Data Compared with Actual Data in the year 2009.

Month	Electricity Consumption (kWh)	
	Actual Use in 2009	Simulation
January	208,980	265,704
February	224,400	251,498
March	258,280	297,455
April	275,740	276,036
May	324,240	333,229
June	384,660	338,807
July	371,210	334,860
August	400,820	353,737
September	418,230	323,596
October	349,380	317,671
November	296,280	293,468
December	230,640	253,116
In Total	3,742,860	3,639,177

The error of the total yearly energy consumption between simulated results and the actual data was 2.8%. The measured monthly energy consumption was within 15% of the simulated monthly energy consumption. This demonstrates that the predictions were in good agreement with the actual energy consumption data of the CYC Building. Thus this modeling and simulation technique can be used for the evaluation of different energy conservation retrofits and their energy performance analysis. This error should be also considered in the measurement and verification process.

There are four ECMs applied to the CYC project: lighting system retrofit; window film; green roof; and chilled plant and related building management system upgrading. To evaluate and analyze the result of each retrofit, the research compared the existing building's energy consumption with each retrofit respectively while the other four aspects keeping the same. At last, the research also compared the existing building's energy consumption with the one after all four retrofits applied in order to study the integrated effect.

- Lighting System Retrofits

LEDs with 35W power were to be installed in the CYC Building to replace the original T8 lightings. The lighting power density before and after the Lighting retrofit were calculated in Table 7. Figure 5 compares the simulation result of the annual energy consumption breakdown by LED energy efficient lamps with the base model. From the simulation result, it can be seen that after the lighting system retrofit, the cooling consumption and the interior lighting consumption were reduced by 16% and 44%, respectively.

Table 7. Lighting Power Density for the existing condition and after the lighting retrofit.

Item	Before (W/m^2)	After (W/m^2)
Lecture/meeting/library room	12	8
Office	10	6
Laboratory	14	8
Service/rest Room	8	4
Corridor/staircase	4	4
Lobby	8	4

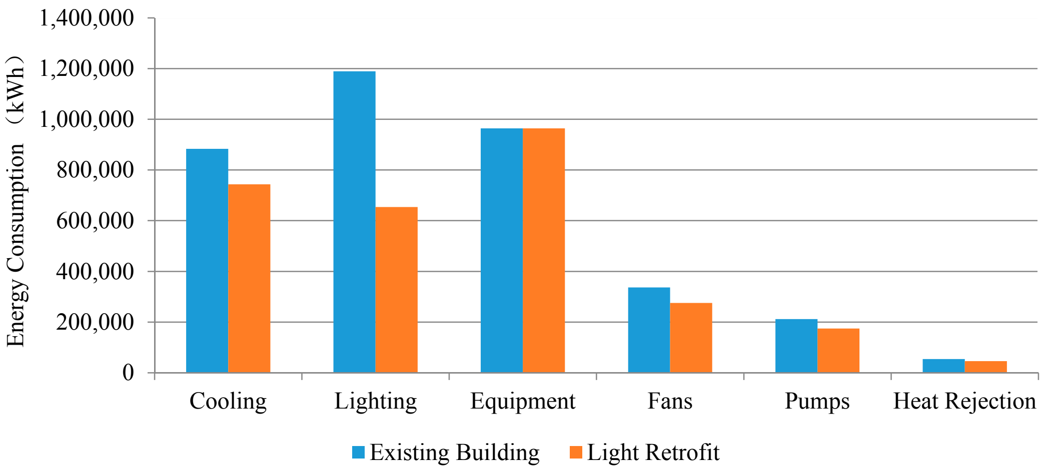

Figure 5. Annual energy consumption before and after the lighting retrofit.

- Window Film

In the CYC Building, some windows were to be coated with the 3M NV 35. The specifications of the original glazing and window film coated glazing are shown in Table 8. From the simulation results as shown in Figure 6, it can be seen that after the window film coating, the cooling consumption and the fans energy consumption were reduced by 6% and 6.5%, respectively.

Table 8. Glazing specifications in the base model and retrofit model.

Glazing Properties	Before the Retrofit	After the Retrofit
WWR	25.60%	25.60%
U-Value (W/m^2·K)	6.148	1.06
Solar Heat Gain Coefficient (SHGC)	0.82	0.38
Total Solar Transmission	0.82	0.38
Direct Solar Transmission	0.79	0.25
Light Transmission	0.881	0.35
Shading Coefficient	0.9	0.49

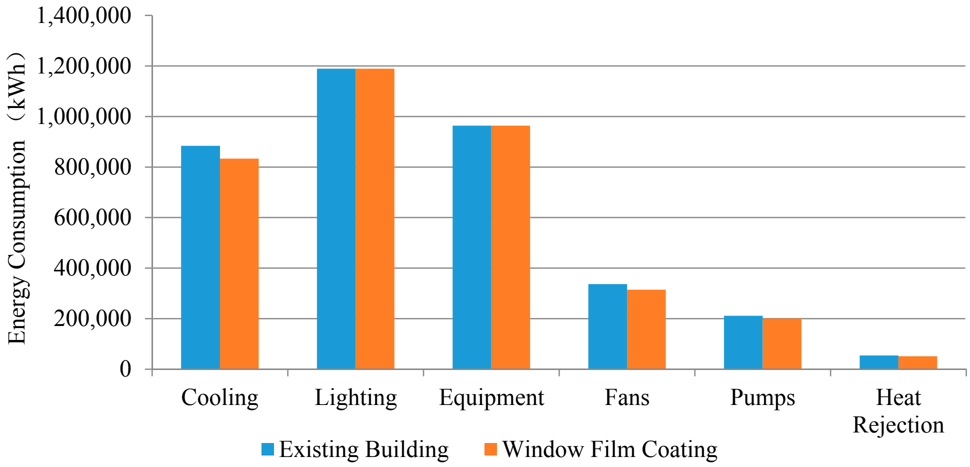

Figure 6. Annual energy consumptions before and after the windows coating.

- Green Roof

In the CYC Building, an intensive green roof system was designed to reduce solar radiation on the original flat concrete roof. Table 9 shows the specification of the green roof system. From the simulation results as shown in Figure 7, it can be seen that after greening the roof, the annual energy consumption was not reduced obviously. It might because the area of the green roof was too small (only 100 m^2) and it did not have much influence on the whole building's energy consumption.

Table 9. Specification of the green roof.

Item	Value
Area (m^2)	100
Thickness (m)	0.15
Conductivity of Dry Soil (W/m·K)	0.35
Specific heat of Dry Soil (J/kg·K)	1200
Thermal Absorptance	0.9
Solar Absorptance	0.7
Leaf Reflectivity	0.22
Leaf Emissivity	0.95
Minimum Stomatal Resistance (s/m)	180

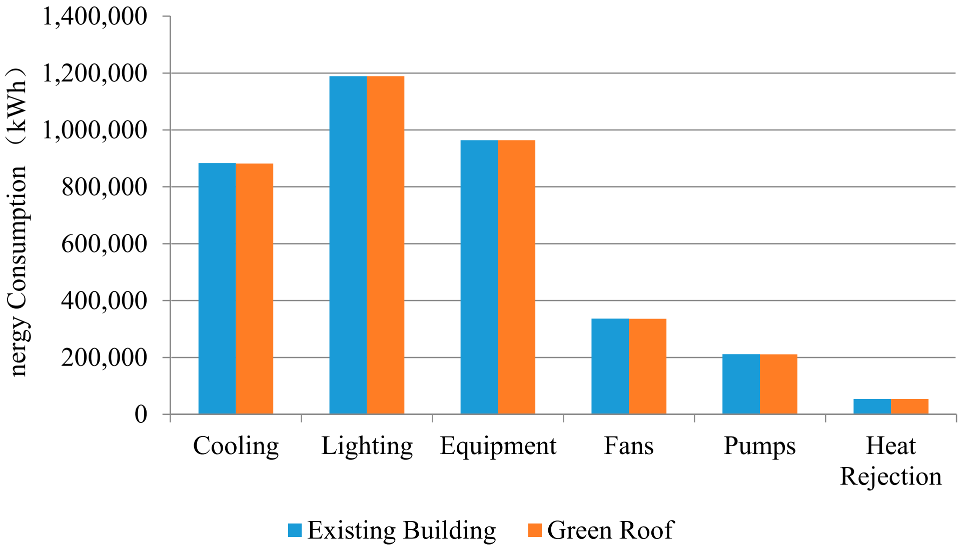

Figure 7. Annual energy consumption before and after the roof retrofit.

- Chiller Plant Upgrading

The COP of chiller plant was to be updated from 2.6 to 5.0 by the plant replacement. Table 10 compares the monthly electricity consumption due to this upgrade. As shown in Figure 8, chiller plant updating can reduce a significant portion of cooling load in summer, especially in June, July, August, September and October. The cooling energy consumption was reduced by 27.4%.

- Combined Energy Conservation Measures

From the simulation results (Figure 9), it can be seen that after combining the four measures, the cooling consumption and the interior lighting consumption were reduced by respectively 42% and 45%. The total energy saving was 1,256,259 kWh per year which could be translated to a reduction of 853 tons of CO_2 emission per year.

Table 10. Cooling electricity consumptions before and after the upgrade.

Month	Before	After
	Chiller Plant COP 2.6	Chiller Plant COP 5.0
9 January	46,124	23,842
9 February	44,057	22,962
9 March	58,912	38,983
9 April	68,289	50,264
9 May	86,855	68,016
9 June	96,128	75,128
9 July	98,358	78,464
9 August	100,339	79,330
9 September	91,727	71,764
9 October	81,298	61,512
9 November	62,998	44,396
9 December	48,598	26,243

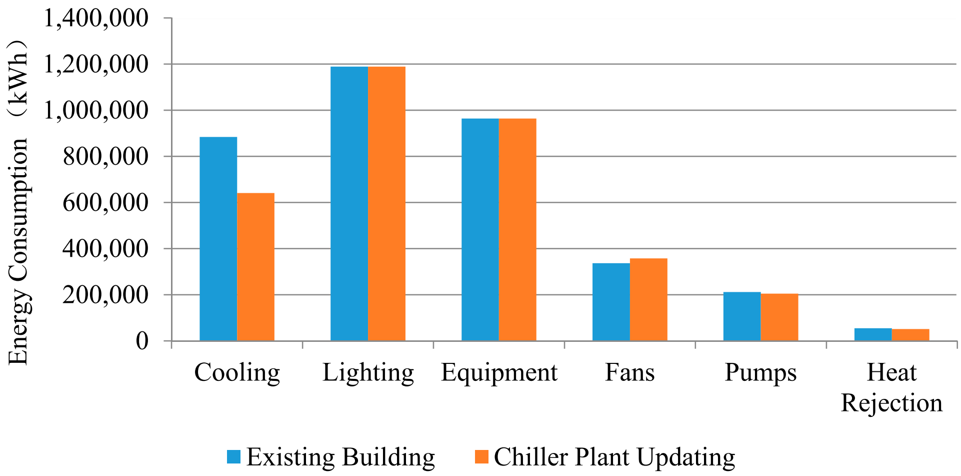

Figure 8. Annual energy consumption before and after the chiller plant upgrading.

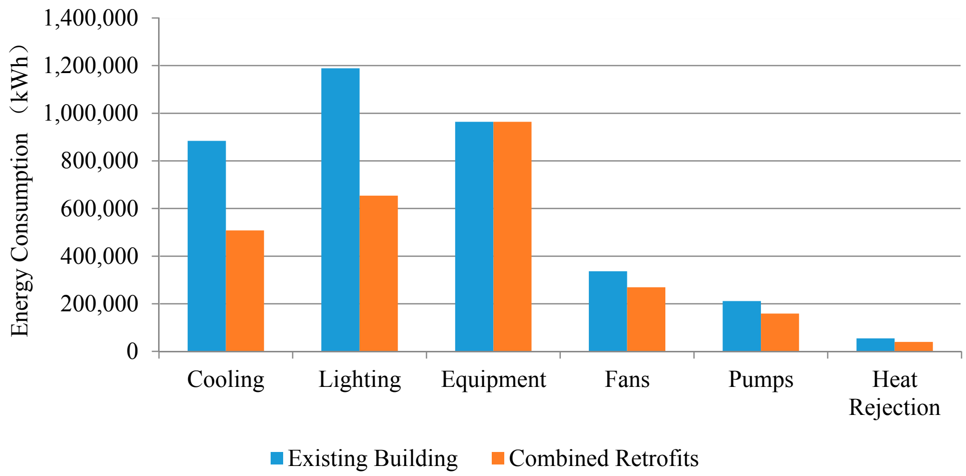

Figure 9. Annual energy consumption before and after the combined retrofits.

3.3. Measurement and Verification

The determination of energy savings requires both accurate measurement and replicable methodology, known as a measurement and verification protocol. Based on the M & V protocol [40], this project measured and verified the effectiveness of isolated retrofit strategy as well as energy use of the whole retrofitted building.

The M & V of the lighting retrofit was conducted before and after the retrofit. The M & V chose three areas to do the comparison study before and after the retrofit: study area, rest area and kitchen area. The three areas were measured several times before and after retrofits under artificial illumination only. A CHROMA Meter CL-200 (Konica Minolta Sensing Americas, Ramsey, Inc., NJ, USA) was used to measure illuminance levels. The result is disclosed in Figure 10. After the retrofit, the illuminance was increased at the same place. The M & V also tested 30 T8 tubes (the main lighting sources before the retrofit) and 30 LED tubes (the main lighting sources after the retrofit). The average wattage of LED tubes was 35 W and that of T8 tubes was about 67 W, which means that LED saved more electricity to achieve the same illuminance level.

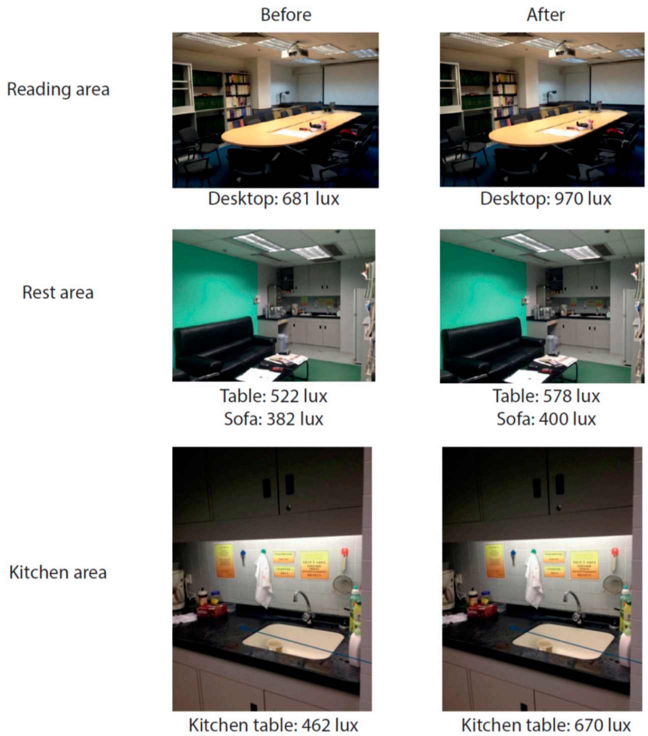

Figure 10. Lighting before and after the retrofit.

Most windows were tinted with films to reduce solar heat gains; however, while some of windows were kept unchanged for comparison. M & V was conducted to compare transmission properties of windows with and without films. This measurement was conducted on 21 October 2012 during 12:00–13:00 p.m. The windows on each façade north, south, east and west were selected to conduct the measurement. A Solar Transmission & BTU Power Meter (EDTM SP2065, EDTM, Inc., Toledo, OH, USA) was used to measure the two types of windows on each façade. Figure 11 shows the comparative study; it indicates that the windows with films significantly reduced the solar heat gains.

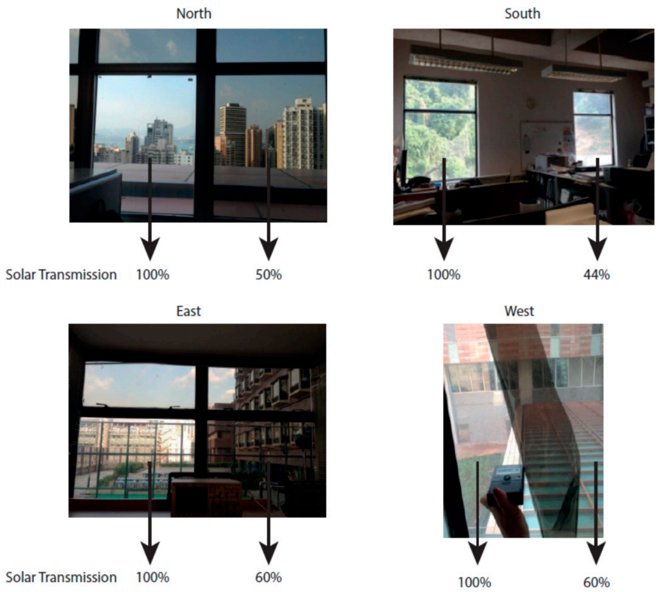

Figure 11. Solar transmission comparisons between windows with and without films.

The retrofitting was completed in 2012. Energy use data for the year 2014 were collected. Through the comparison of the actual energy use data before and after the retrofit, the energy savings could be verified. Figure 12 compares the monthly electricity bill of the year 2009 and that of the year 2014 as well as the simulation result. It is observed that the energy use after the retrofit was reduced from 2009 to 2014. However, the reduction was not that significant as the simulation predicted. Figure 13 further summarizes the three results and found that the simulation expected 30% energy saving while the actual energy saving was 16%. There was still 14% gap between the real energy reduction and the simulated reduction. The simulation validation study mentioned in Section 3.2 showed that there was some error (15%) in the simulation result, which might explain the performance gap. Kaplan and Canner [41] suggested the difference between the predicted energy consumption by simulation and the actual energy consumption data fall into the range of 10% to 25%. Xu et al. [42] suggested that the acceptable error for building simulation model when using ASHRAE standard should be within 5% for monthly energy data.

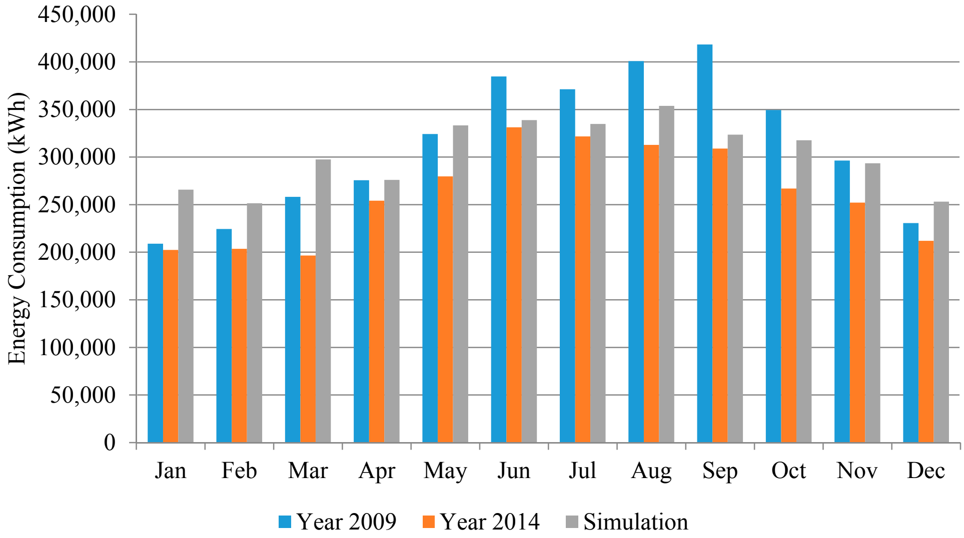

Figure 12. Monthly electricity use in the year 2009, 2014 and the simulation result.

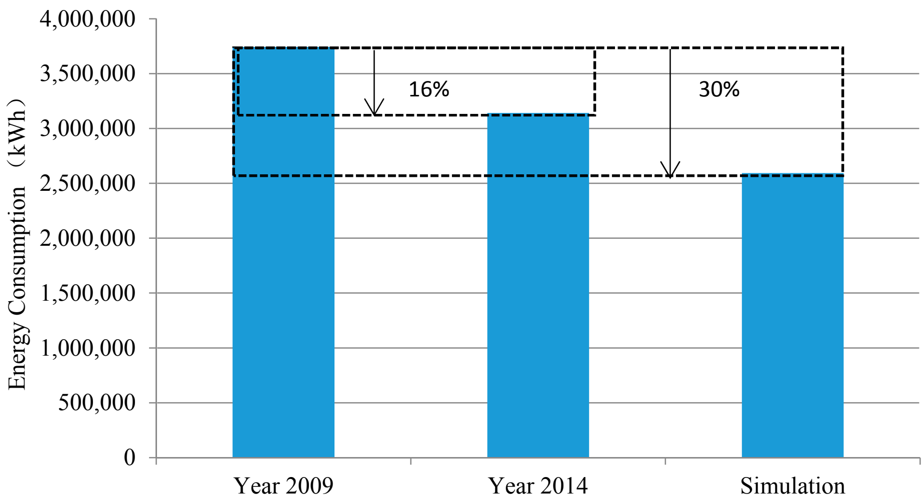

Figure 13. Total electricity use in the year 2009, 2014 and the simulation result.

4. Discussion

From this case study, the strengths and weaknesses of the key stages of the retrofit project can be summarized as in Table 11. Energy auditing is the foremost part of a retrofit process to identify the ECMs. It is based on direct evidence: visual inspections and direct utility costs. However, it does not tell the effectiveness of the ECMs. Therefore, it should be followed by the next stage: building performance simulation to analyze and compare the ECMs. The concern is that the energy audit is confined to budget and manpower and the selection of ECMs consequently may miss some opportunities. For example, in this project, due to the budget and manpower limitations, only four ECMs were selected. To better identify ECMs, a stakeholder approach is recommended to reduce the risks of missing opportunities. The stage of building performance simulation is instrumental in analyzing and comparing the selected ECMs; based on the analysis, the effectiveness and outcome of ECMs can be estimated. However, the building simulation has a large variety of parameters and complexity of factors such as non-linearity, discreteness, and uncertainty. In this study, it is found that the building simulation overestimated the energy savings through the ECMs. The main reason for this overestimation is occupancy condition. In simulation, the assumed occupancy hours are 9am-5pm; while in reality, overtime working is normal in both academic offices and laboratories. This accounted for the overestimation of energy reduction. It is almost impossible to precisely predict the real occupancy condition. Therefore, the energy simulation for retrofitting should be flexible to accommodate this unpredictability. Furthermore, although the building simulation can provide results corresponding to what the user inputs, they cannot provide suggestions to improve design [24]. Finally, the measurement and verification stage verifies the effectiveness and outcomes predicted by the building simulation. It can compare the physical environments and utility costs before and after the retrofit. The concern is that there are many factors (including occupancy condition change) contributing to the variation of the before- and after- performances. Therefore, to find out the reasons for the success or failure, the non-building factors should be controlled.

Table 11. SWOT analysis of the key retrofitting stages.

Key Stages	1. Energy Auditing	2. Building Simulation	3. Measurement & Verification
Objectives	Identify ECMs	Analyze ECMs	Examine ECMs
Strengths	Direct evidence	Prediction	Direct evidence
Weaknesses	Lack of assumptions	Uncertainties	Generality
Opportunities	Combined with building simulation	Calibration with electricity bills	Compare with pre-retrofit bills and simulations
Threats	Missing opportunities	Overestimating energy savings	Missing specific reasons for success and/or failure

The rigorous process demonstrated typical energy efficiency practice on commissioning analysis and implementation, which helped this project achieve the LEED EBOM Gold certification. The four ECMs, too, helped to reduce the energy uses to achieve the credits in "Optimize Energy Performance". However, the four ECMs were confined to active strategies (mainly mechanical systems) while there were no significant passive strategies such as natural ventilation and daylighting which could significantly reduce energy demanding, which handicapped this project for further achievement towards a higher certification level such as Platinum.

5. Conclusions

This research described the detailed process of the retrofitting and energy conservation measurements of a LEED EBOM project. Through this project, a systematic method of energy efficient retrofits for existing buildings can be concluded and applied to other projects. This case study demonstrated that the energy audit and analysis process provided detailed information to choose the optimized energy conservation measures for existing buildings. Energy conservation measures were proposed on lighting, chiller plant, windows and green roof. The building computer simulation evaluated the energy saving for each energy conservation measure. Specifically, the lighting retrofit was expected to achieve 21% energy saving; the chiller plant COP increase from 2.6 to 5 was expected to reduce 7% of the total energy use; window film coating was expected to reduce 3% of the energy consumption; while a green roof with little area had no significant influence on the energy consumption. After the retrofit, the measurement and verification process was conducted to verify the outcome. As a result, in the year after the retrofit, the CYC building energy consumption has reduced by 16% which is an obvious success to reduce the energy use. However, there is still 14% gap. The gap was similar to the error of 15% found in the simulation calibration using electricity bills. Occupancy condition such as overtime working has been found as the main reason for the gap [43,44].

Although the project successfully reduced the energy consumption by 16% through the green retrofitting, it was scope for even more energy efficiency compared to the green building standard. There are more opportunities for this building to push its energy performance. Particularly, most retrofit measures proposed in this project were active design strategies focusing on building services or fixed envelope components; passive measures, such as natural ventilation and daylighting which could be more effective in reducing energy consumption were not considered in this project, [45]. Of course, these strategies might have limited application in high-rise high-dense urban environments with hot humid climates. Further studies are needed to look at more radical retrofitting measures to significantly reduce building energy consumptions in a cost-effective way.

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Abbreviations

AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMS	Building Management System
COP	Coefficient of Performance
EBOM	Existing Buildings: Operations & Maintenance
ECMs	Energy Conservation Measures
FCU	Fan Coil Unit
GFA	Gross Floor Area
HVAC	Heating, Ventilation and Air-Conditioning
IEQ	Indoor Environment Quality
kWh	Kilowatt Hours
LEED	Leadership in Energy and Environmental Design
LED	Light Emitting Diode
LPD	Lighting Power Density
M & V	Measurement & Verification
PAU	Pre-cooling Air Unit
SHGC	Solar Heat Gain Coefficient
VF	Ventilation Fans

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