International Journal of Science and Engineering Invention (IJSEI)
Volume 11, Issue 02, April 2025
https://doi.org/10.23958/ijsei/vol11-i02/280

Research Article

Post-Retrofit Performance Assessment of Administrative Building: Energy, Comfort, and Carbon Emissions

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Received 16 March 2025; Accepted 15 April 2025; Published 20 April 2025

Abstract

Retrofitting existing buildings for improved energy performance is increasingly recognized as a cost-effective and sustainable strategy to reduce energy consumption and greenhouse gas emissions, particularly in regions with intensive cooling demands (Al-Tamimi, 2022; Alrashed & Asif, 2015). This study presents a detailed, three-year post-retrofit performance evaluation of a government administrative complex located in Riyadh, Saudi Arabia. The retrofit intervention involved three buildings totalling 45,597 m² and included a suite of energy saving measures (ESMs) such as chilled water system optimization, packaged air-conditioning unit upgrades, and advanced lighting controls, all integrated through a centralized building management system (BMS) (Al-Mofeez & Al-Sallal, 2017).

The measurement and verification (M&V) process was conducted in accordance with the International Performance Measurement and Verification Protocol (IPMVP), employing both Options A and B to assess system-level and whole-building impacts. The facility's baseline energy consumption was established at 6.43 GWh annually, with a guaranteed savings commitment of 1.86 GWh (28.89%). Across the three-year performance period, actual energy savings consistently exceeded projections: 2.02 GWh (31.7%) in Year 1, 1.95 GWh (31.12%) in Year 2, and 2.01 GWh (31.59%) in Year 3. These savings were achieved without the need for non-routine adjustments, reflecting the reliability and persistence of the retrofit measures. Cumulatively, the project yielded nearly 6.0 GWh in energy savings and substantial economic benefits, with annual utility cost reductions ranging between SAR 600,000 and 650,000 (Al-Mofeez & Al-Sallal, 2019).

The results confirm the technical and financial viability of performance-based retrofit projects in hot-climate institutional buildings, while also highlighting the effectiveness of a robust M&V framework (Krarti & Ihm, 2016; Al-Shehri & Al-Homoud, 2005). This study contributes practical evidence to support policy and investment decisions in energy efficiency programs across the public sector, particularly in high-growth, climate-stressed regions.

Keywords: ***Building retrofit, Energy efficiency, Performance verification, IPMVP, HVAC optimization, public buildings, Hot climate.***

Introduction

Buildings account for a substantial portion of global energy consumption and greenhouse gas (GHG) emissions, making them critical targets for decarbonization strategies and national energy efficiency agendas (AlHashmi *et al.*, 2021). In hot climates, such as those found across the Middle East and North Africa (MENA) region, cooling-related electricity demand dominates building energy profiles, placing considerable strain on both grid infrastructure and national energy budgets. Retrofitting existing buildings-through targeted energy saving measures (ESMs) has emerged as a cost-effective and scalable solution to reduce operational energy use, enhance occupant comfort, and meet long-term sustainability goals (Al-Shehri & Al-Homoud, 2004).

In Saudi Arabia, the building sector contributes over 70% of total electricity consumption, with the commercial and institutional segments experiencing significant pressure to modernize aging infrastructure (Al-Tamimi, 2022). The facility under study which is located in Riyadh exemplifies this challenge. Comprising three main buildings namely the Main Building, Old Building, and IT Building spanning a combined footprint of 45,597 m², the facility is a high-occupancy, weekday-operational complex reliant on a variety of HVAC systems including chillers, chilled water pumps, AHUs, FAHUs, package units, and a mix of split and window air-conditioning systems. Prior to retrofit implementation, the total annual energy consumption was calculated at approximately 9.47 GWh (FY 2019-2020), with associated electricity bills exceeding 3.0 million SAR (Al-Shehri & Al-Homoud, 2003).

To address these inefficiencies, a multi-faceted energy retrofit project was undertaken. The core objective was to minimize electricity usage without compromising comfort levels, primarily by automating equipment operations through the deployment of a centralized Building Management System (BMS) (Al-Sallal & Al-Rais, 2012). The retrofit package included chiller optimization, time scheduling and set-point control of package units, installation of variable frequency drives (VFDs) and pressure independent control valves (PICVs) on pumps, and lighting upgrades with smart control systems. These ESMs were strategically selected to target both peak and base loads, offering a guaranteed annual energy savings of 1.86 GWh (28.89%). The consumption pattern at the facility is distributed as shown in the figure below:

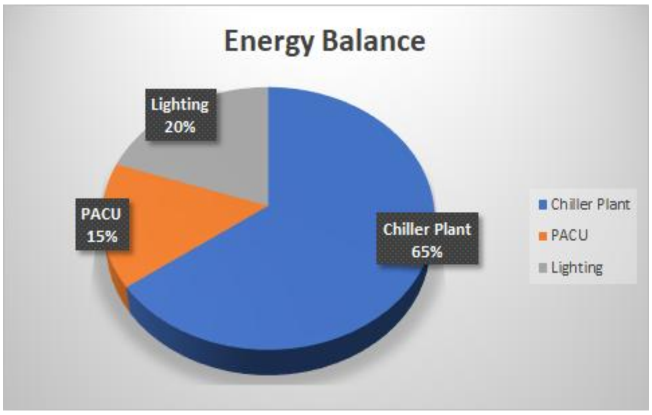

Figure 1: Energy balance

This paper presents a comprehensive post-retrofit performance evaluation of a facility over a continuous three-year period, using a robust Measurement and Verification (M&V) methodology consistent with the International Performance Measurement and Verification Protocol (IPMVP). By applying Options A and B, the study quantifies system-level and whole-building energy performance, evaluates occupant comfort, and estimates the corresponding reduction in carbon emissions. The results demonstrate sustained performance gains across all years, validating the long-term reliability of the retrofit measures and their potential for replication in similar public-sector buildings in arid, high-energy-intensity climates.

Methodology

Overview of M&V Options and Measurement Boundaries

To ensure accurate quantification of energy savings while maintaining cost-effectiveness and practicality, two M&V options were selected:

- **Option A (Retrofit Isolation** - Key Parameter Measurement) was used for lighting optimization ESMs, where only the power (kW) of lighting fixtures was directly measured, and operating hours were estimated based on occupancy data and space usage.
- **Option B (Retrofit Isolation** - All Parameter Measurement) was adopted for all HVAC-related ESMs, including chillers, chilled water pumps, packaged air-conditioning units (PACUs), and associated fans, where both energy consumption and operating conditions were continuously monitored using sub-meters (IPMVP, 2012; Krarti & Ihm, 2016).

Option A: Lighting Optimization (ESM 4 & ESM 5)

ESM Description and Scope

Two lighting ESMs were implemented:

- ESM 4: Replacing legacy fluorescent lighting fixtures with high-efficiency LED lamps and drivers.
- ESM 5: Installing occupancy sensors to reduce operating hours via intelligent control.

The lighting system covered all three buildings, with replacement and control strategies tailored to specific usage zones such as offices, corridors, service areas, and meeting rooms (AlHashmi *et al.*, 2021).

Measurement Boundary

The measurement boundary for Option A encompassed the entire lighting system. The key parameter lighting fixture power consumption was measured using a statistically significant sample (covering over 75% of total fixtures). Power ratings were validated against manufacturers' specifications and physical measurements. Operating hours were estimated based on occupancy behaviour, assessed via HOBO data loggers. Data from sensors across multiple usage groups were analysed using HOBO Savings Analysis Tool (Al-Mofeez & Al-Sallal, 2019), yielding an average savings potential of 51%, later conservatively adjusted to 30% due to a 31.3% uncertainty margin.

Baseline Energy Use and Savings Calculation

The lighting baseline energy consumption was determined through detailed inventory analysis and usage profiling. The savings from both lighting replacement and controls were calculated as follows:

- Lighting Replacement (ESM 4): $\Delta kWh = kWh\_baseline - kWh\_proposed$
- Lighting Control (ESM 5): $\Delta kWh = Power\_LED \times (Operating\ hours\_baseline - Operating\ hours\_post\text{-}retrofit)$

The combined savings from ESM 4 and 5 amounted to 831,165 kWh annually, corresponding to a 45.3% reduction from the lighting baseline.

Option B: HVAC System Optimization (ESM 1, 2, & 3)

ESM Description

Option B was applied to measure savings from HVAC-related interventions, including:

- ESM 1.1: Chiller optimization systems
- ESM 1.2/1.3: Control upgrades for Exhaust Fans, FAHUs, and weather stripping
- ESM 2: Installation of VFDs and PICVs on chilled water pumps
- ESM 3: Time scheduling and setpoint optimization for PACUs and associated air-handling systems

Sub-metering systems were installed on all relevant equipment including chillers (north and south), PACUs, and pumps (Krarti & Ihm, 2016).

Baseline Development and Statistical Modelling

Baseline energy use was derived from 12-month pre-retrofit metered data (December 2020 - December 2021). A regression analysis was performed against cooling degree days (CDD) using consumption data with a base temperature of 18°C. Strong correlations were found between energy consumption and CDD:

- Chiller North: $kWh = 383.15 \times CDD + 36114$ ($R^2 = 0.968$)
- Chiller South: $kWh = 375.75 \times CDD + 39503$ ($R^2 = 0.96$)
- PACUs (10 units): $kWh = 170.89 \times CDD + 3603.91$ ($R^2 = 0.818$)

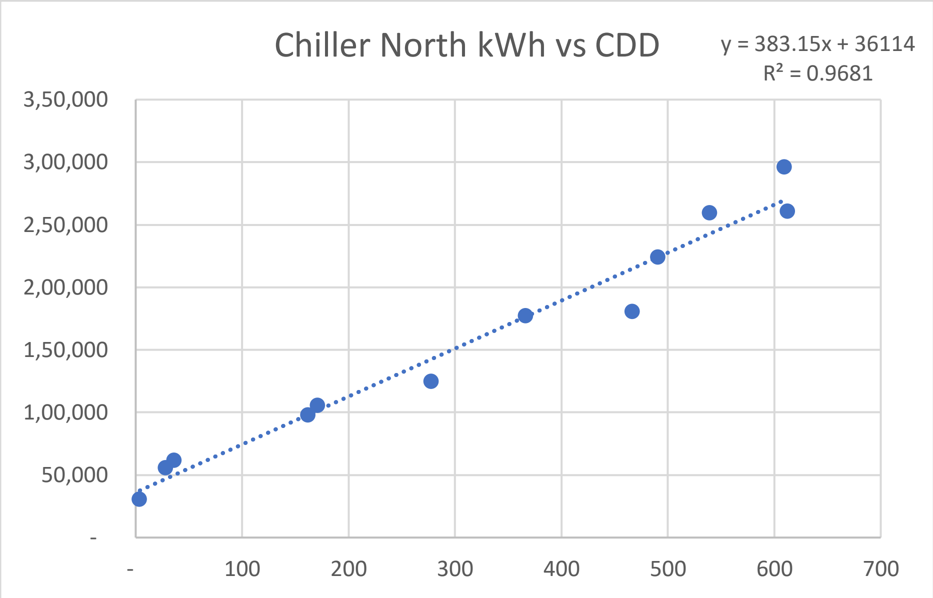

Fig 2: Chiller (North) Regression Model

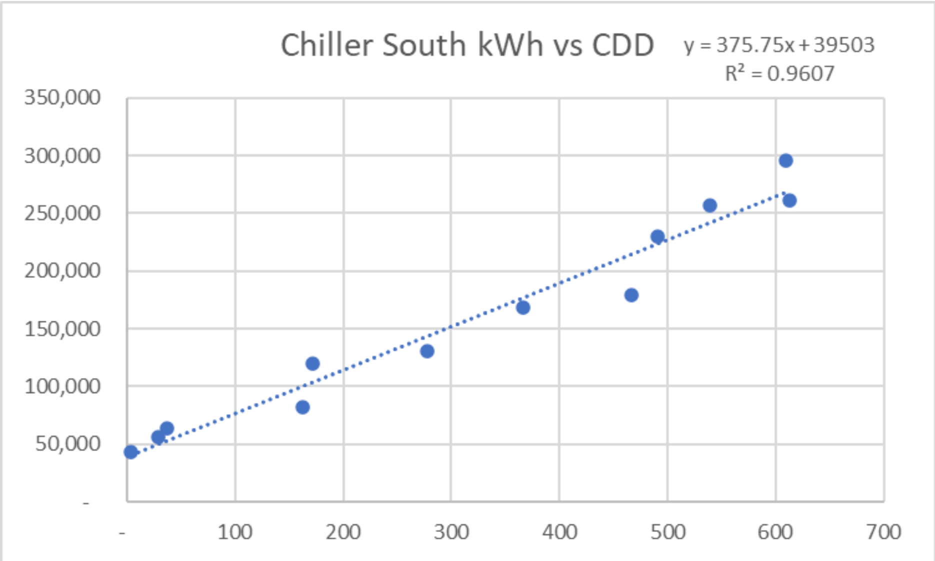

Fig 3: Chiller (South) Regression Model

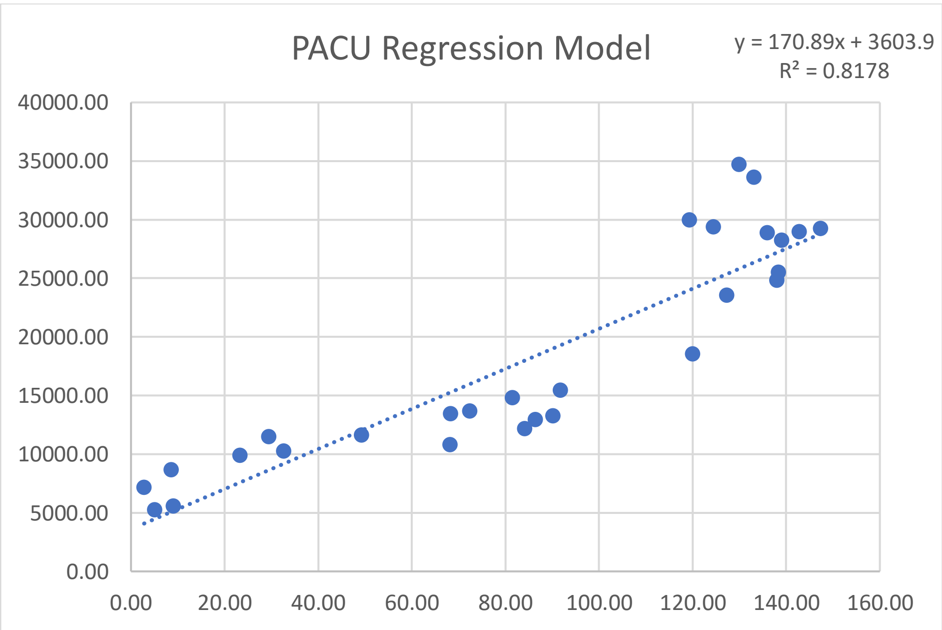

Fig 4: Regression model for PACU

These regression models were used for routine baseline adjustments during performance evaluation.

Option B involved direct measurement of energy use at the equipment level over the post-retrofit period. Savings were computed as the difference between the adjusted baseline and actual consumption:

Savings = Baseline_adjusted - Consumption_reporting_period

No non-routine adjustments were necessary during the three-year performance period.

Accuracy and Uncertainty Analysis
Each model's standard error and confidence interval were calculated to validate savings estimates per IPMVP requirements. The uncertainties at a 90% confidence level were well within acceptable limits:

- Chillers: ~16-18% uncertainty, $R^2 > 0.9$
- PACUs: ~17.5% uncertainty, $R^2 = 0.82$

All models satisfied IPMVP criteria for statistical accuracy and were used to reliably quantify savings over the performance period.

Static Factors and Adjustments

Static factors such as occupancy rates, operational hours, and equipment load profiles were documented during the baseline development and remained unchanged throughout the evaluation period. No significant operational or usage changes occurred, thus eliminating the need for non-routine adjustments.

Routine adjustments primarily temperature-related (CDD) were integrated into the regression-based models for chillers and PACUs.

Results

This section presents the measured energy savings performance over three consecutive years following the implementation of energy efficiency retrofits at an administrative complex in Riyadh. The evaluation includes a breakdown of monthly and annual energy savings from both lighting and HVAC systems, their relation to cooling degree days (CDD), and a comparative performance analysis across the years (Al-Mofeez & Al-Sallal, 2018).

Annual Energy Savings
Energy savings were evaluated using IPMVP Options A (lighting systems) and B (HVAC systems), across three full years from December 2021 to December 2024. The performance was assessed with respect to the adjusted baseline, with no non-routine adjustments (NRA) applied in any year.

Table I. Savings Year wise

Performance Year	CDD (18°C)	Option B Savings (kWh)	Option A Savings (kWh)	Total Savings (kWh)	Savings % w.r.t. Adjusted Baseline
Year 1 (2021-2022)	3,701.6	1,040,854	978,709	2,019,563	31.70%
Year 2 (2022-2023)	3,602.1	979,751	974,606	1,954,357	31.12%
Year 3 (2023-2024)	3,674.0	1,035,518	971,305	2,006,822	31.59%

Across all three years, the facility consistently exceeded the guaranteed annual savings target of **1,857,823 kWh**, maintaining an average savings rate of approximately **31.47%**. The cumulative savings over the performance period amounted to **5,980,742 kWh**, representing a strong and sustained outcome (Alrashed & Asif, 2015; Al-Tamimi, 2022).

Seasonal and Monthly Performance Trends
Monthly savings patterns revealed strong seasonal variability driven by ambient temperature and cooling demand (CDD), especially for HVAC systems (Alrashed & Asif, 2014).

Peak Summer Periods (April-September)

- **Cooling load-intensive months** consistently showed higher savings from chillers and PACUs.
- For example, in **May 2022**, **245,088 kWh** was saved (40.51%), and in **June 2023**, **220,017 kWh** was saved (29.47%).

Winter and Shoulder Seasons (November-February)

- Savings percentages were highest in these periods due to reduced base load and stable lighting contributions.
- Notably, **January 2023** achieved a **58.47%** savings rate despite zero cooling demand (CDD = 0), indicating dominant savings from lighting control (ESM 5) and optimized schedules.

Performance of Energy Saving Measures (ESMs)

Option A: Lighting Systems

- Delivered an average of **974,873 kWh/year** (49% of total savings).
- The lighting replacement (ESM 4) achieved stable baseline reduction, while occupancy-based controls (ESM 5) ensured consistent off-peak savings.
- Highest lighting savings occurred in **low-CDD months**, indicating effective automation regardless of seasonal demand (AlHashmi *et al.*, 2021; Al-Shehri & Al-Homoud, 2004).

Option B: HVAC System Optimization

- Contributed an average of **1,018,707 kWh/year** (51% of total savings).
- Peak savings occurred in high-CDD months (May-August), with **chiller optimization (ESM 1.1)** and **PACU time scheduling (ESM 3)** playing critical roles.

Table II. Year-on-Year Comparison and Stability

Indicator	Year 1	Year 2	Year 3
Total Savings (kWh)	2,019,563	1,954,357	2,006,822
Chillers + PACU (Option B)	1,040,854	979,751	1,035,518
Lighting (Option A)	978,709	974,606	971,305
Average Monthly Savings (kWh)	168,297	162,863	167,235
Savings % (Annual)	**31.70%**	**31.12%**	**31.59%**

Performance remained remarkably consistent across all three years. Slight fluctuations in savings correlated with minor variations in cooling degree days and HVAC runtime but were not statistically significant. No deviations or underperformance were observed against the guaranteed targets (Al-Shehri & Al-Homoud, 2003; Al-Sallal, 2016).

Cost Savings and Economic Impact

Based on the prevailing electricity tariffs in the Eastern Region of Saudi Arabia, the project achieved annual cost savings estimated between SAR 600,000 and SAR 650,000. Over a three-year period, this equates to a cumulative financial saving of approximately SAR 1.9 million, demonstrating a strong return on investment (Al-Mofeez & Al-Sallal, 2019). In addition to economic benefits, the reduction in electricity consumption also led to a decrease in carbon emissions. Using the regional emission factor of approximately 0.7 kg CO_2 per kWh, the project avoided an estimated 850 to 920 metric tons of CO_2 emissions annually, contributing significantly to environmental sustainability goals.

Summary of Findings

- **Energy savings exceeded contractual guarantees each year**, with zero reliance on non-routine adjustments.
- **Lighting and HVAC retrofits contributed nearly equally**, providing redundancy and stability across seasons.
- **Performance remained stable and robust**, despite fluctuating weather conditions, validating the reliability of installed automation and controls.
- The project demonstrates the **long-term viability of energy retrofits** in large administrative facilities operating in hot-arid climates (Al-Shehri & Al-Homoud, 2005; Al-Sallal & Al-Rais, 2012).

Discussion

A three-year performance evaluation was conducted to quantify the energy savings achieved from the retrofit interventions at the administrative facility. The analysis focuses on the contributions from HVAC-related measures (captured under Option B: chillers and PACU systems) and lighting improvements (captured under Option A), with performance benchmarks referenced to the adjusted baseline energy consumption. No non-routine adjustments (NRA) were required during any of the evaluation periods.

This study provided a thorough, three-year post-retrofit performance assessment of an administrative building complex situated in Riyadh, Saudi Arabia. The retrofit project targeted improvements in energy efficiency, operational control, and indoor comfort through the implementation of integrated Energy Saving Measures (ESMs), including HVAC system optimization and lighting upgrades, all governed by a centralized Building Management System (BMS) (Al-Mofeez & Al-Sallal, 2017).

The facility, comprising three buildings with a combined area of 45,597 m², was subjected to continuous performance monitoring using the International Performance Measurement and Verification Protocol (IPMVP), applying both Options A and B. This enabled robust measurement of system-level and whole-building energy savings, grounded in empirical data and supported by statistically validated models. Over the course of three years, the results consistently exceeded the guaranteed savings target of 1.86 GWh annually (28.89%), with actual annual savings ranging between 1.95-2.02 GWh and average savings of ~31.47% across the entire period.

Year-1 Performance (26 December 2021 to 25 December 2022)

In the first performance year, the facility experienced a total of 365 days with an accumulated Cooling Degree Days (CDD) value of 3701.6. The detailed savings were as follows:

- Chiller Savings (ESMs 1 & 2): 889,739 kWh
- PACU Savings (ESM 3): 151,116 kWh
- Lighting Savings (ESM 4 & 5, Option A): 978,709 kWh
- Combined Savings (Option B - including HVAC components): 1,040,854 kWh
- Total Savings (Including all measures): 2,019,563 kWh

The overall savings corresponded to a 31.7% reduction with respect to the adjusted baseline energy consumption. This performance level clearly demonstrated that the retrofit measures not only met but exceeded the guaranteed savings targets. The breakdown further indicates that the HVAC systems, particularly the chiller components, contributed the largest share to the overall savings.

Table III. Saving Achieved Year-1

From	To	No. of days	CDD	Chillers Savings (ESM 1,2)	PACU Savings (ESM 3)	Option B Savings	Option A Savings Lighting (ESM 4,5)	NRA	Total savings including NRA	Savings % w.r.t Adjusted Baseline
			18 C	kWh	kWh	kWh	kWh	kWh	kWh	%
26/12/21	25/01/22	31	7.9	36,671	5,555	42,226	83,123	0	125,349	49.21%
26/01/22	25/02/22	31	24.7	38,133	1,630	39,763	83,123	0	122,886	45.45%
26/02/22	25/03/22	28	138.4	55,606	3,420	59,026	75,079	0	134,105	37.31%
26/03/22	25/04/22	31	292.6	112,804	6,768	119,572	83,123	0	202,695	39.02%
26/04/22	25/05/22	30	390.5	146,417	18,229	164,646	80,442	0	245,088	40.51%
26/05/22	25/06/22	31	563.6	94,798	11,424	106,222	83,123	0	189,345	24.54%
26/06/22	25/07/22	30	572.7	105,942	41,781	147,723	80,442	0	228,165	29.47%
26/07/22	25/08/22	31	609.9	71,756	24,354	96,110	83,123	0	179,233	22.01%
26/08/22	25/09/22	31	516.7	83,843	21,663	105,505	83,123	0	188,629	25.92%
26/09/22	25/10/22	30	327.8	57,844	7,780	65,624	80,442	0	146,065	26.72%
26/10/22	25/11/22	31	203.3	49,658	8,769	58,427	83,123	0	141,550	32.43%
26/11/22	25/12/22	30	53.5	36,267	-255	36,012	80,442	0	116,453	39.94%
Total		**365**	**3701.6**	**889,739**	**151,116**	**1,040,854**	**978,709**	**0**	**2,019,563**	**31.7%**

Year-2 Performance (26 December 2022 to 25 December 2023)
During the second year, the facility operated for 365 days with a slightly lower total CDD of 3602.1. The energy savings observed were:

- Chiller Savings (ESMs 1 & 2): 773,176 kWh
- PACU Savings (ESM 3): 206,575 kWh
- Lighting Savings (ESM 4 & 5, Option A): 974,606 kWh
- Combined HVAC Savings (Option B): 979,751 kWh
- Total Savings: 1,954,357 kWh

The overall savings for Year-2 were 31.12% relative to the adjusted baseline. A notable observation in this year was a decrease in chiller-related savings compared to Year-1; however, this was offset by a significant increase in the PACU savings. The consistency in the lighting systems' performance was maintained, which is reflected in the relatively stable savings between the two years.

Table IV. Saving Achieved Year-2

From	To	No. of days	CDD	Chillers Savings (ESM 1,2)	PACU Savings (ESM 3)	Option B Savings	Option A Savings Lighting (ESM 4,5)	NRA	Total savings including NRA	Savings % w.r.t Adjusted Baseline
			18 C	kWh	kWh	kWh	kWh	kWh	kWh	%
12/26/2022	1/25/2023	31	0	62,173	-298	61,875	82,775	0	144,650	58.47%
1/26/2023	2/25/2023	31	28.3	71,323	7,189	78,512	82,775	0	161,287	58.93%
2/26/2023	3/25/2023	28	125.6	49,029	9,004	58,033	74,764	0	132,797	38.21%
3/26/2023	4/25/2023	31	190.9	89,250	14,089	103,340	82,775	0	186,115	43.80%
4/26/2023	5/25/2023	30	397.1	97,232	31,574	128,806	80,105	0	208,910	34.19%
5/26/2023	6/25/2023	31	537	104,571	32,671	137,242	82,775	0	220,017	29.47%
6/26/2023	7/25/2023	30	577	85,387	22,449	107,835	80,105	0	187,940	24.15%
7/26/2023	8/25/2023	31	615.4	23,760	31,380	55,140	82,775	0	137,915	16.83%
8/26/2023	9/25/2023	31	548	49,530	25,876	75,406	82,775	0	158,181	20.90%
9/26/2023	10/25/2023	30	382.6	63,182	15,722	78,904	80,105	0	159,009	26.61%
10/26/2023	11/25/2023	31	168.2	49,504	11,190	60,695	82,775	0	143,469	35.53%
11/26/2023	12/25/2023	30	32	28,234	5,728	33,962	80,105	0	114,067	42.00%
Total		**365**	**3602.1**	**773,176**	**206,575**	**979,751**	**974,606**	**0**	**1,954,357**	**31.12%**

Year-3 Performance (26 December 2023 to 25 December 2024)
In the final monitored year, the facility recorded 366 days with a CDD value of 3674. The energy performance during this year was characterized by the following savings:

- Chiller Savings (ESMs 1 & 2): 780,850 kWh
- PACU Savings (ESM 3): 254,667 kWh
- Lighting Savings (ESM 4 & 5, Option A): 971,305 kWh
- Combined HVAC Savings (Option B): 1,035,518 kWh
- Total Savings: 2,006,822 kWh

The resultant savings percentage was 31.59% when compared with the adjusted baseline. Year-3 showed a slight recovery in chiller savings and a continued increase in PACU savings relative to Year-2. The combined performance of HVAC systems and lighting retrofits continued to deliver savings consistent with the guaranteed targets.

Table V. Saving Achieved Year-3

From	To	No. of days	CDD	Chillers Savings (ESM 1,2)	PACU Savings (ESM 3)	Option B Savings	Option A Savings Lighting (ESM 4,5)	NRA	Total savings including NRA	Savings % w.r.t Adjusted Baseline
			18 C	kWh	kWh	kWh	kWh	kWh	kWh	%
12/26/23	01/25/24	31	21.3	40,752	16	40,768	82,269	0	123,037	46.05%
01/26/24	02/25/24	31	38.7	61,755	10,493	72,248	82,269	0	154,517	54.53%
02/26/24	03/24/24	28	91.4	75,366	10,781	86,147	74,307	0	160,455	50.82%
03/25/24	04/24/24	31	209.6	82,916	17,949	100,865	82,269	0	183,134	41.41%
04/25/24	05/24/24	30	376	110,501	23,791	134,292	79,615	0	213,907	36.17%
05/25/24	06/24/24	31	600.1	107,427	45,485	152,912	82,269	0	235,181	29.20%
06/25/24	07/24/24	30	596	53,371	38,280	91,651	79,615	0	171,266	21.52%
07/25/24	08/24/24	31	608	57,847	37,357	95,205	82,269	0	177,474	21.84%
08/25/24	09/24/24	31	539.6	25,610	42,024	67,634	82,269	0	149,903	20.01%
09/25/24	10/24/24	30	378	68,067	19,645	87,712	79,615	0	167,327	28.20%
10/25/24	11/24/24	31	180.1	51,078	17,357	68,435	82,269	0	150,704	36.33%
11/25/24	12/25/24	31	35.4	46,158	-8,511	37,647	82,269	0	119,916	42.78%
Total		**366**	**3,674**	**780,850**	**254,667**	**1,035,518**	**971,305**	**-**	**2,006,822**	**31.59%**

Conclusion

Comparative Analysis and Insights

Across the three evaluation periods, the total annual energy savings were remarkably consistent, averaging around 2.0 GWh and consistently exceeding the baseline savings percentage of approximately 31%. Key observations from the results are:

- **Robust HVAC Performance:** The chiller system savings exhibited some year-to-year variability (from 889,739 kWh in Year-1, declining to 773,176 kWh in Year-2, and recovering to 780,850 kWh in Year-3). This variability is primarily attributed to fluctuations in cooling loads and ambient conditions, as indicated by slight differences in CDD values.
- **Enhanced PACU Savings:** The PACU savings improved notably from 151,116 kWh in Year-1 to 254,667 kWh in Year-3, highlighting an increasing performance impact of optimized package units over time.
- **Consistent Lighting Savings:** The lighting retrofit measures delivered consistent savings (close to 975,000 kWh annually) across all three years, underpinning the stability of Option A's performance.
- **Stable Overall Savings with No Adjustments:** The absence of non-routine adjustments (NRA = 0 across all years) indicates that the retrofitted systems have maintained their designed performance parameters over the evaluation period. This reliability reinforces the robustness of the installed Building Management System (BMS) and associated controls.
- **High Confidence in Savings Estimates:** The savings, measured using both Options A and B, consistently met or exceeded the specified guaranteed targets, thereby validating the effectiveness of the integrated retrofit strategy and the applied M&V framework.

Overall, the consistent performance across three years, despite minor variations in specific components, confirms the technical and economic viability of the retrofit measures implemented at the facility. The results provide a strong case for the scalability of such energy efficiency interventions in similar administrative buildings situated in hot-arid climates.

Implications and Recommendations

This research provides compelling evidence that performance-based energy retrofits in public sector administrative buildings are both technically viable and financially attractive. The successful implementation demonstrates that:

- Deep retrofitting with intelligent controls and equipment-specific optimizations can yield sustained long-term savings.
- A well-structured M&V protocol enables performance assurance, which is critical for building trust among stakeholders and funding bodies.
- These strategies are replicable in similar buildings across the region, particularly in climates with high cooling loads (Al-Sallal, 2015; Alrashed & Asif, 2015).

It is recommended that future retrofit projects adopt a similar integrated approach combining ESM selection with predictive modelling, dynamic monitoring, and adaptive control to ensure continued performance. Additionally, coupling energy savings data with occupant comfort and indoor environmental quality metrics will help further enhance the value proposition of energy efficiency retrofits.

List of Abbreviations

GHG: Green House Gases
ESM: Energy Saving Measures
BMS: Building Management System
M&V: Measurement & Verification
IPMVP: International Performance Measurement and Verification Protocol
GWh: Gigawatt Hour
FY: Fiscal Year
IT: Information Technology
HVAC: Heating, Ventilation, and Air Conditioning
AHU: Air Handling Unit
FAHU: Fresh Air Handling Units
PACU: Packaged Air Conditioning Unit
VFD: Variable Frequency Drives
PICV: Pressure Independent Control Valves
kW: Kilowatt
kWh: Kilowatt hour
CDD: Cooling Degree Days
LED: Light Emitting Diode
NRA: Non-Routine Adjustments
m^2: Square Meter
SAR: Saudi Riyal

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