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Temporal Energy Signatures in Tropical Mixed-use Buildings: an IoT-Driven Framework for Occupancy-Responsive Management

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ABSTRACT

Keywords
Cloud- IoT system
Energy management system
Occupancy-driven energy management
Tropical building energy behavior
Renewable energy integration

Rising energy demand in rapidly urbanizing Indonesia necessitates efficient management strategies for mixed-use buildings. This study implements a cloud-IoT platform (ennexOS®) to monitor high-resolution ($5 - min\ interval$) electricity consumption and solar generation ($18.36\ kWp\ PV$) across two educational buildings in West Java ($2023 - 2024$). Analysis quantified three key insights, such as a Stable annual grid consumption ($729.78\ MWh$) despite marginal PV generation growth ($1.92 \rightarrow 2.07\ MWh$), a Seasonal fluctuation driven by climate ($*r* = 0.51$ with temperature) and occupancy (e.g., Ramadan), with peak demand in October ($75.17\ MWh$) and minimum demand in April ($42.14\ MWh$), and Diurnal regimes revealing occupancy-dominant patterns: nighttime baseline (00:00-06:00), daytime surge ($07{:}00 – 18{:}00$), and evening decline ($18{:}00 – 24{:}00$), with residential HVAC sustaining 43.4% of total load. Results demonstrate cloud-IoT's critical role in profiling energy behavior for targeted interventions (e.g., occupancy-responsive HVAC, pump optimization). The framework enables future machine-learning integration for predictive management in tropical climates. Findings advocate scalable IoT deployments to advance Building Energy Management Systems (BEMS) in mixed-use environments, directly supporting high-impact publication avenues focused on sustainable urbanization and smart infrastructure.

1. Introduction

Rising energy demand in mixed-use buildings, particularly within Indonesia's rapidly urbanizing context, necessitates innovative solutions for efficient management and increase the environmental awareness. This study addresses this challenge by designing, implementing, and analysing a Cloud Based IoT System for real-time Energy Monitoring System to understand Building Energy Behaviour in two integrated educational multi-purpose buildings in West Java, Indonesia. The system integrates real-time electricity consumption monitoring via SMA Energy Meters with energy generation data from an $18.36\ kWp\ PV$ Rooftop system, utilizing the commercial Cloud Based IoT System platform ennexOS (Sunny Portals®) for data aggregation, visualization, and storage.

Over a two-year period (January 2023 - December 2024), the Cloud Based IoT System captured high-resolution (5-minute interval) data on both energy consumption and solar generation. This rich dataset enabled a detailed analysis of Building Energy Behavior across different timescales (daily, monthly, yearly) and occupancy conditions (workdays, holidays, peak vs. low activity). Key findings reveal energy consumption behavior, with identifiably strongly influenced by academic calendars, national holidays, and climatic conditions. Daily analysis showed distinct patterns based on repetitive hourly activities in days, and several occupancy-driven habit gaps occur. Workdays (Mon-Fri) consistently consumed more energy than weekends due to office activity. Analysis identified that majority of energy use was occupancy-driven while low consumption events highlighted the inherent utility base load. This study answers the challenge in looking-up the critical value of cloud-based IoT monitoring for precise energy profiling, enabling targeted efficiency measures (e.g., optimized HVAC scheduling, pump operation) and fostering occupant awareness. It establishes a robust foundation for future integration with machine learning to advance predictive energy management and smart building operations in tropical climates

2. Literature Study

The adoption of Internet of Things (IoT) technology in building management has been widely recognized as a revolutionary tool for real-time energy consumption monitoring in commercial buildings [1], [2], [3]. Extensive research on energy management in vertical buildings (e.g., multi-story campuses) [4], [5], [6]within educational institutions has been conducted globally[7]. This focus stems from the education sector's potential to serve as a pilot domain for sustainable

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energy management practices while functioning as a pedagogical and research platform for students[8], [9], [10]. Such initiatives enable practical insights into efficient energy usage in buildings, equipping learners with academically and professionally valuable skills before entering the workforce.

Previous studies have explored IoT integration for developing smart energy management systems [11], [12], highlighting the promise of conceptual platforms in this field. However, validation under real-world operational conditions remains limited. To address this gap, our research advances IoT-driven solutions by implementing hour-level data accuracy in physical building measurements. This approach enables precise monitoring of energy management behavior, establishing a novel reference framework for future applications.

3. Method

This study employed a three-phase approach to analyze energy management behavior across two mixed-use educational buildings (13,520 m^2 $total\ area$) in West Java, Indonesia, as illustrated in **Error! Reference source not found.**. The first phase is A cloud-based IoT Energy Management System (EMS) that was deployed using a commercial platform.

Followed by the second phase, an Automated measurements of energy consumption and generation were collected at $5 - minute$ intervals over a $24 - month$ period. Raw datasets were subsequently aggregated into hourly, daily, weekly, and monthly resolutions to facilitate multi-scale temporal analysis.

And the latest phase of Behavior Analysis Framework is comprised three analytical components, such as (i) Temporal Profiling, that a Comparative analysis of consumption versus generation across daily and seasonal cycles, accounting for distinct occupancy modes (workdays vs. holidays), (ii) Occupancy-Driven Diagnostics. that identify the energy patterns with scheduled peak and low-occupancy periods derived from academic calendars and significant events, and (iii) Granular Regime Analysis that a High-resolution comparison of energy profiles on days exhibiting extreme activity levels to identify specific patterns in occupant behavior and equipment usage.

The integrated methodological workflow is illustrated in **Error! Reference source not found.**. This approach enabled precise identification of operational baselines, quantification of occupancy-driven demand surges, and detection of efficiency opportunities within the tropical mixed-use building context.

3.1. Building Characteristics and Occupancy

This study analyzed two primary structures in an Indonesian educational complex that consist of a 7-Story Dormitory Building and a Public building with total area $13.500 m^2$. The 7-Story Dormitory Building contains 98 rooms with a max capacity of 392 occupants, and the current average 95% occupancy rate. While the primary load of each room has 1.4 kW AC units per room, LED lighting, a $10A$ power outlets. The Public Building contains a 4-story mixed-use facility (offices, public spaces, sports complex, with a workday occupancy of around 80 people. The Primary load of the public building is Split-type AC systems + general lighting/equipment. The Educational complex also includes shared campus infrastructure such as, a $2700\ kVA$ electrical transformer, a $30\ kW$ water pump system, CCTVs, lighting, and other public equipment. And an $18.6\ kWp$ grid-tied PV system (**Error! Reference source not found.**) was installed across rooftops to supplement clean energy.

3.2. The development of cloud-based IOT system

The commercial SunnyPortals®/ennexOS cloud platform was deployed for real-time energy monitoring, shown in **Error! Reference source not found.**. Electrical consumption data was captured via three-phase CT sensors and SMA Energy Meters, while generation data was recorded from the $15\ kWp$ PV system as depict on **Error! Reference source not found.**. All data streams (consumption + generation) transmitted at 5-minute intervals to the cloud.

Data management utilized the EnnexOS of Sunny Portals® interface as a Real-time energy flow visualization platform, with capabilities in *.csv data exports automatically, and may maintain $24 - month$ datasets (Jan 2023-Dec 2024) as a data storage. This will help the study acquire adequate dataset consistently.

4. Result and Discussion

The cloud-IoT monitoring system quantified energy dynamics across two mixed-use buildings over $2023 - 2024$ with adequate visualization that helps the user in capture energy flow a cross the building as show in **Error! Reference source not found.** and yet revealing three key insights, such as.

- Total cumulative energy, consumption grid energy use remained stable at $729.78\ MWh$ across both years. While the total energy generation an averaged $1.92\ MWh$ in year 2023 and $2.07\ MWh$ in year 2024. The cloud-IoT performance seamlessly in recording data and precisely analyze the energy flow (consumption vs generation) as shown in Raw data of energy consumption and energy generated in 2 years within this 2 years;
- Seasonal Patterns, Analysis of two years of data reveals distinct seasonal patterns in energy behavior. Energy consumption peaked in October (maximum: $75.17\ MWh\ in$ 2024), while the lowest demand occurred in April (minimum: $42.14\ MWh\ in$ 2023) as seen on **Error! Reference source not found.**. These patterns demonstrate significant climate-driven variability, exhibiting a positive correlation with ambient temperature ($*r* =$ 0.51; Figure 8a). The pronounced demand reduction in April coincides with the Islamic holy month of Ramadan, a period of extended holiday leading to reduced building occupancy and consequently lower energy usage. Furthermore, humidity data showed a moderate correlation with average energy generation (Figure 8b). The seasonal analysis also highlights differing consumption profiles between weekdays (Monday-Friday) and weekends (Saturday-Sunday), as displayed in

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Error! Reference source not found.. Weekday consumption is predominantly driven by combined residential occupancy and office activities, whereas weekend usage is primarily applicable to residential occupancy alone;

- Occupant behavior pattern, Further analysis examined residential occupancy and office operation behavior patterns over a $24-hour$ period on days exhibiting extreme energy consumption. Hourly energy consumption profiles for a representative high-consumption day (October 16, 2024) and a representative low-consumption day (April 5, 2024) are presented in Figure 10. This comparison identifies distinct temporal patterns in occupancy and associated equipment usage, enabling in-depth analysis of their influence on energy demand during peak and minimum load conditions.

4.1. Energy behaviour analysis & Discussion

Distinct weekday-weekend consumption patterns are evident in Figure 9. Weekday demand (peaking at $2.900\ kWh/day$) reflects the additive load from combined residential occupancy and office operations. A pronounced mid-week peak (Wednesday–Thursday) suggests cumulative operational intensity prior to weekend reductions. Consumption on non-productive days (Saturday–Sunday) ranged between $2.000–2.300\ kWh/day$, consistent with loads traceable solely to residential occupancy. A significant consumption reduction occurred during Week 3 of April 2024 ($831\ kWh/day$), corresponding to the week-long Ramadan holiday period. This represents the building's operational baseline load, comprising essential utility functions (e.g., water pumps, transformer standby losses) under near-zero occupancy conditions.

Analysis of secondary ambient climate data (BPS Bekasi City) revealed a moderate positive correlation (Pearson'$s * r *=$ 0.51) between energy consumption and daily air temperature (Figure 8a), indicative of increased cooling demand during warmer periods. Conversely, on-site PV energy generation trends exhibited an association with humidity patterns (Figure 8b), which often correlate with cloud cover and precipitation, suggesting atmospheric conditions influence renewable output efficiency.

On **Error! Reference source not found.** presents a comparative diurnal energy profiles for April $5, 2024$ (Wednesday) and October $16, 2024$ (Wednesday), selected as representative periods of minimum and maximum occupancy/activity, respectively. Wednesdays were chosen based on prior analysis indicating peak weekly occupancy. Three distinct diurnal consumption regimes are identified:

- Nighttime Baseline ($00:00–06:00$): Consumption reflects essential system operation (transformer losses, minimal lighting, intermittent water pumps). The elevated baseline observed on October 16th highlights the influence of supplementary HVAC usage driven by occupancy, even during nominal low-demand periods and the drop of ambient temperature during the dawn;
- Morning Surge and Daytime Sustained Load ($07:00–18:00$): A sharp increase in energy consumption commencing at $07:00$ correlates with the activation of occupancy-dependent systems, notably cyclic water pumping (required to meet demand and maintain pipeline pressure) and HVAC operation responding to thermal loads. Peak loads observed within this period arise primarily from the concurrent engagement of these systems, particularly HVAC units and water pumps. Sustained high consumption reflects ongoing operational activities. A gradual decline initiates post-$18:00$ as office functions cease, although significant residential cooling demand persists;
- Evening Decline ($18:00–24:00$): Consumption decreases post-18:00 as office occupancy ends. However, significant residential HVAC demand (especially cooling) moderates the decline rate, illustrating the divergent energy behaviors between commercial and residential uses within the mixed-use building and the influence of thermal comfort preferences during evening hours.

These regimes are shaped by occupancy patterns, infrastructure requirements, and the hybrid building function. The nighttime baseline is dominated by fixed losses modifiable via efficiency retrofits. The daytime surge is acutely sensitive to occupancy schedules and concurrent system startups, presenting opportunities for load management and better water management design. The evening phase underscores the substantial impact of residential HVAC. This temporal disaggregation is essential for effective energy optimization models.

Load allocation analysis as shown in **Error! Reference source not found.** indicates residential activities contribute 43,4% of total consumption, followed by utilities (34,8%) and office operations. This profile provides precise data for building energy management system (BEMS) optimization, suggesting several strategies, such as:

- Occupancy-Responsive Controls: Implement behavioral interventions ("Saving Energy" awareness, equipment shut-down protocols) and schedule-based adjustments for HVAC/lighting during holidays/academic breaks;
- Utility Optimization: Extend water tank capacity to reduce pump cycling frequency and associated power spikes, coupled with water conservation measures ("Saving water" initiatives) and deployment of IoT-based automated water actuation systems;
- Renewable Integration: Utilize historical generation data and humidity correlations to develop short-term (e.g., 2-day ahead) PV generation forecasting, enhancing both daily operational optimization and long-term energy management control strategies.

5. Conclusion

This study employed a cloud-IoT monitoring system to quantify energy dynamics across two mixed-use buildings from 2023 to 2024. Analysis revealed three principal insights: (1) Total grid energy consumption remained stable at $729{,}78\ MWh$ annually ($54{,}07 kWh/m2$) , while on-site PV generation increased marginally from $1.92\ MWh$ to $2.07\ MWh$; (2) Distinct seasonal patterns emerged, with peak demand in October ($75.17\ MWh$ in 2024) and minimum

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demand in April (42.14 MWh in 2023), driven significantly by climate variability ($* r * = 0.51$ with temperature) and occupancy changes during Ramadan; (3) Diurnal analysis identified three occupancy-driven consumption regimes—nighttime baseline ($00{:}00 – 06{:}00$), morning surge/daytime load ($07{:}00 – 18{:}00$), and evening decline ($18{:}00 – 24{:}00$)—with residential HVAC proving particularly influential in sustaining evening demand. Load allocation analysis further determined that residential activities dominated consumption patterns (43.4%), followed by utilities (34.8%) and office operations.

These findings demonstrate the critical influence of occupancy patterns, climate sensitivity, and hybrid building functions on energy profiles. Future work should prioritize: (1) Implementation of occupancy-responsive HVAC/lighting controls and behavioral interventions; (2) Utility optimization through water tank expansion to reduce pump cycling and deployment of IoT-based water management systems; and (3) Development of humidity-correlated PV forecasting models for 48-hour generation predictions. Validation of these strategies through real-world deployment and extension of the monitoring framework to diverse building typologies would significantly advance building energy management systems (BEMS) in mixed-use environments.

Fig 1. Integrated mixed-used buildings

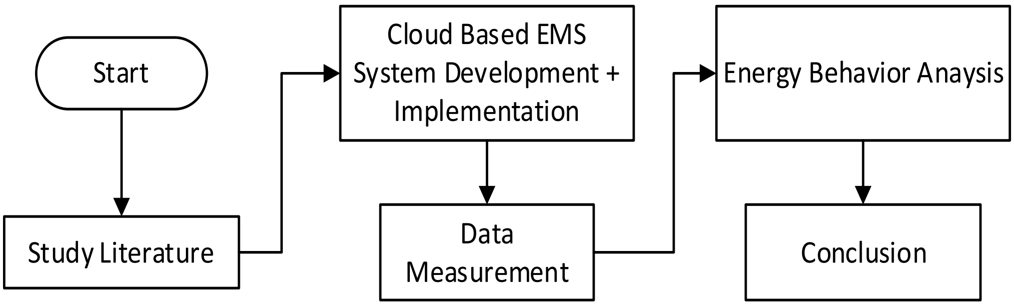


Fig 2. Cloud based IoT in building energy management study approach

a) 18,36kWp PV rooftop b) SMA Inverter 15000TL-30 c) SMA Data Management

Fig 3. PV rooftop and IoT based ems

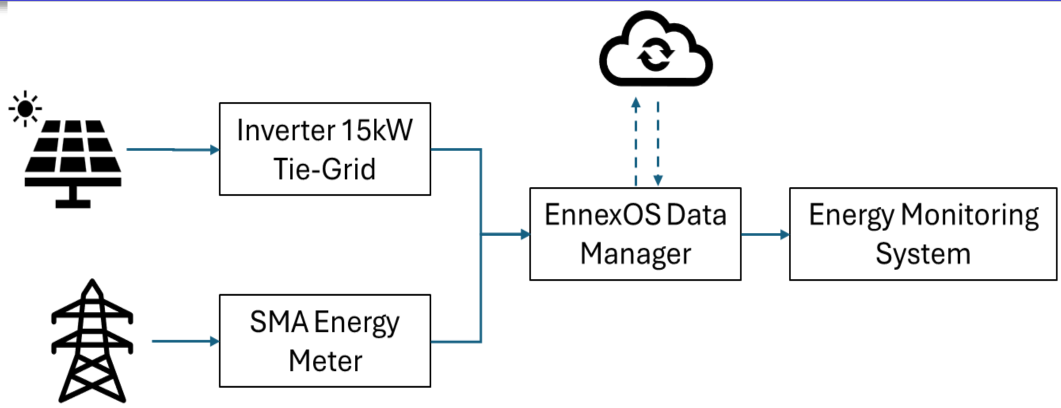


Fig 4. Schematic diagram PV Rooftop and Cloud based energy monitoring system

Table 1. PV rooftop specification

PV Rooftop	*Specification*
Total Power Rated Capacity	18,36 kWp
Total Inverter On-Grid	15 kWP Sunny Tripower 15000TL-30
PV system	34 unit JA Solar 440 Wp
IOT System	SMA Energy Meter – EnnexOs Data

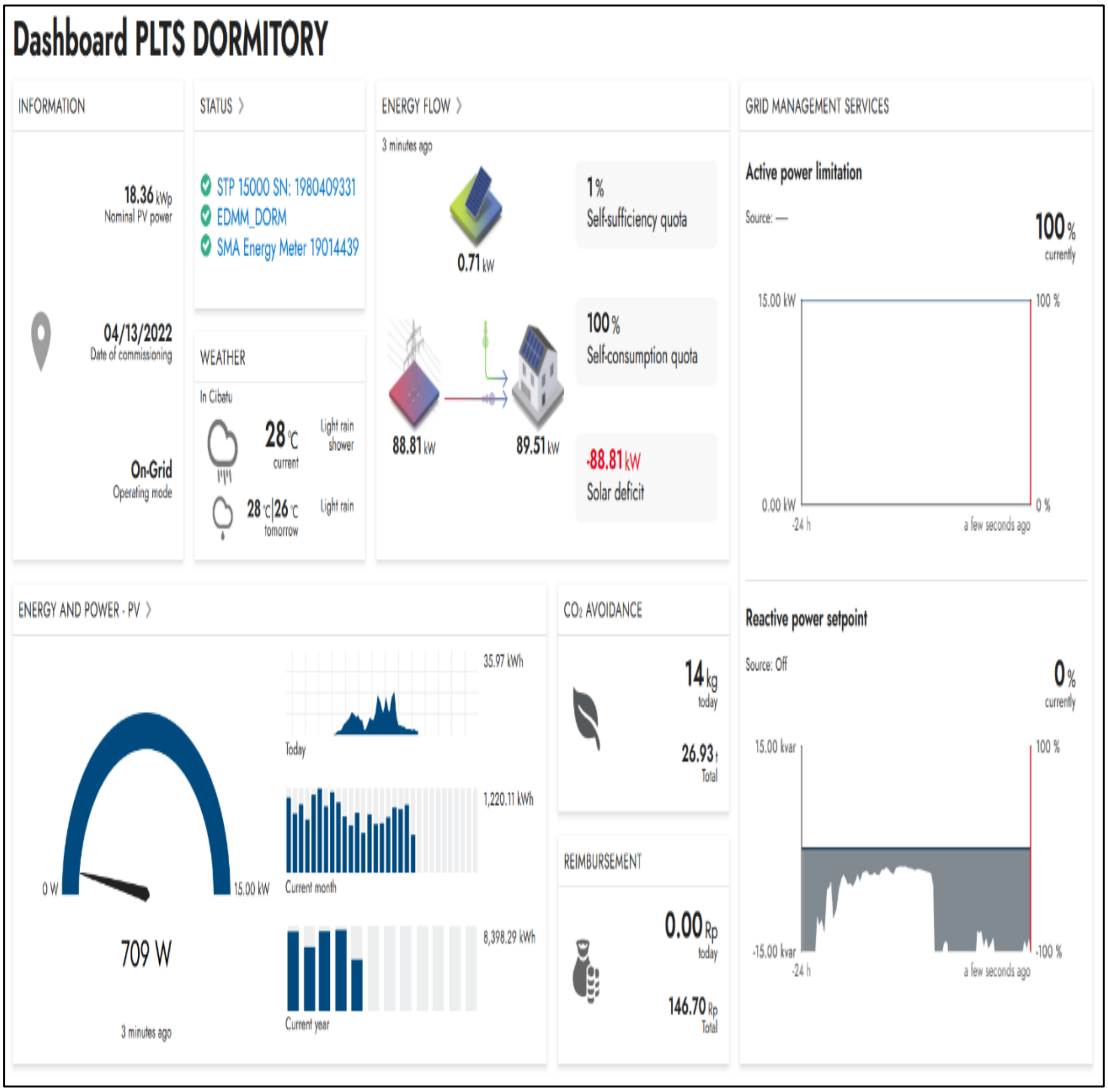


Fig 5. The interface of building IoT ems applications

Time period	Direct consumption [kW]	Grid-supplied power [kW]	Grid feed-in [kW]	Total consumption [kW]	Total generation [kW]
12.05 AM	0	85.96	0	85.96	-
12.10 AM	0	89.11	0	89.11	-
12.15 AM	0	85.24	0	85.24	-
12.20 AM	0	88.89	0	88.89	-
12.25 AM	0	86.87	0	86.87	-
12.30 AM	0	86.81	0	86.81	-
12.35 AM	0	88.49	0	88.49	-
12.40 AM	0	87.09	0	87.09	-
12.45 AM	0	85.29	0	85.29	-
12.50 AM	0	88.17	0	88.17	-
12.55 AM	0	83.99	0	83.99	-
01.00 AM	0	86.71	0	86.71	-
01.05 AM	0	82.38	0	82.38	-
01.10 AM	0	86.93	0	86.93	-
01.15 AM	0	83.32	0	83.32	-
01.20 AM	0	83.66	0	83.66	-
01.25 AM	0	77.61	0	77.61	-
01.30 AM	0	87.97	0	87.97	-
01.35 AM	0	81.14	0	81.14	-
01.40 AM	0	84.09	0	84.09	-
01.45 AM	0	82.92	0	82.92	-
01.50 AM	0	85.64	0	85.64	-
01.55 AM	0	80.83	0	80.83	-
02.00 AM	0	83.47	0	83.47	-
02.05 AM	0	77.76	0	77.76	-
02.10 AM	0	82.6	0	82.6	-
02.15 AM	0	83.57	0	83.57	-
02.20 AM	0	80.02	0	80.02	-
02.25 AM	0	80.27	0	80.27	-
02.30 AM	0	80.57	0	80.57	-
02.35 AM	0	83.58	0	83.58	-
02.40 AM	0	80.23	0	80.23	-
02.45 AM	0	83.34	0	83.34	-
02.50 AM	0	75.91	0	75.91	-
02.55 AM	0	84.52	0	84.52	-
03.00 AM	0	85.2	0	85.2	-
03.05 AM	0	90.35	0	90.35	-
03.10 AM	0	86.7	0	86.7	-
03.15 AM	0	85.14	0	85.14	-
03.20 AM	0	81.88	0	81.88	-
03.25 AM	0	82.65	0	82.65	-
03.30 AM	0	78.68	0	78.68	-
03.35 AM	0	80.84	0	80.84	-
03.40 AM	0	81.75	0	81.75	-
03.45 AM	0	74.29	0	74.29	-
03.50 AM	0	71.31	0	71.31	-
03.55 AM	0	77.81	0	77.81	-
04.00 AM	0	69.59	0	69.59	-
04.05 AM	0	76.95	0	76.95	-

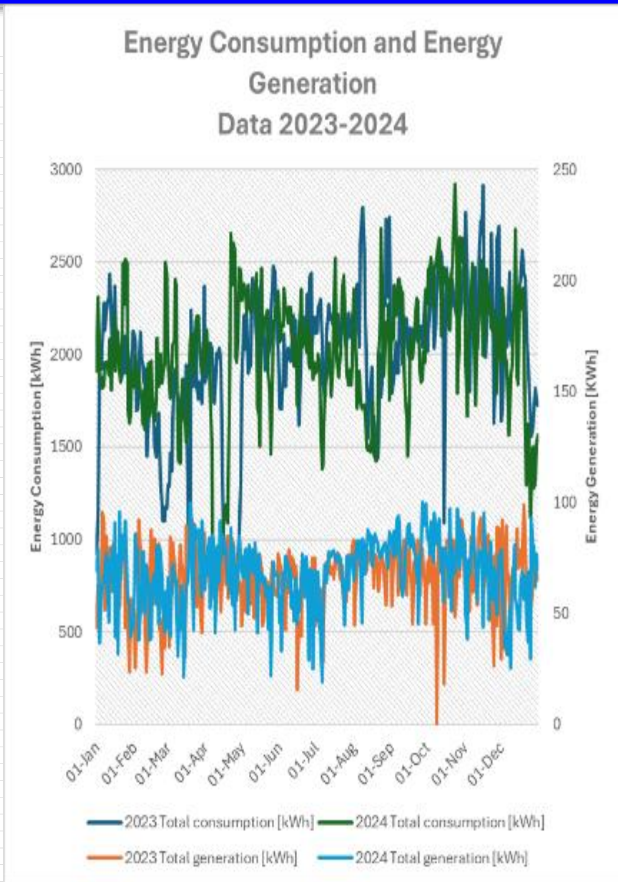
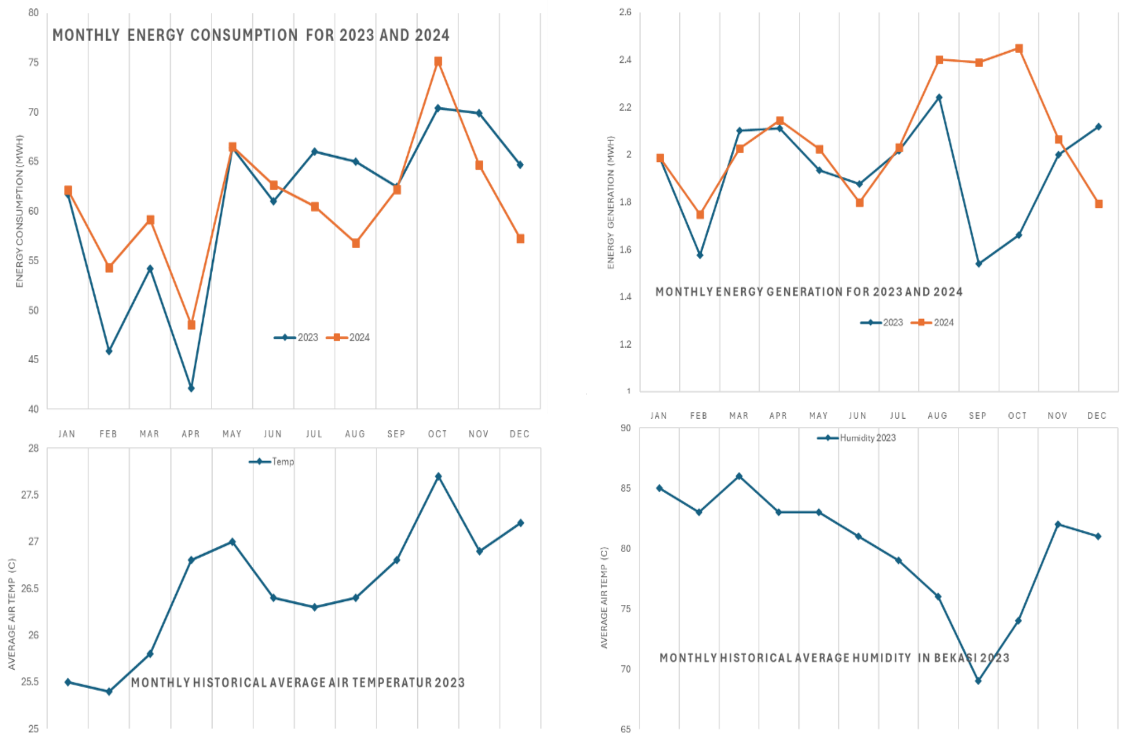


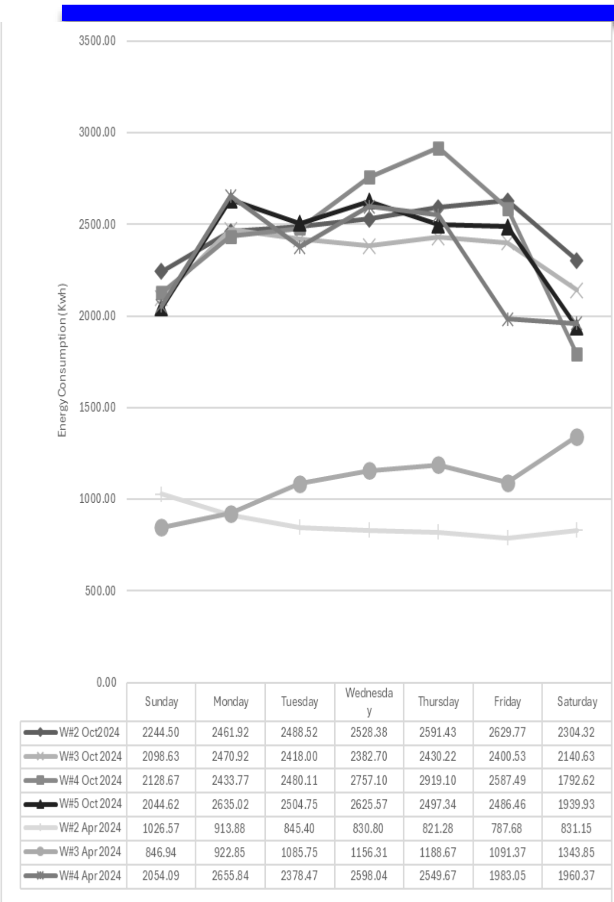
Fig 6. Raw data of energy consumption and energy generated in 2 years



a) Monthly E consumption for 2023-2024 vs Air Temperature in 2023

b) Monthly energy generated for 2023-2024 vs Humidity data in 2023

Fig 7. 2-Years monthly building energy behaviour and climate historical data



	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
W#2 Oct2024	2244.50	2461.92	2488.52	2528.38	2591.43	2629.77	2304.32
W#3 Oct 2024	2098.63	2470.92	2418.00	2382.70	2430.22	2400.53	2140.63
W#4 Oct 2024	2128.67	2433.77	2480.11	2757.10	2919.10	2587.49	1792.62
W#5 Oct 2024	2044.62	2635.02	2504.75	2625.57	2497.34	2486.46	1939.93
W#2 Apr 2024	1026.57	913.88	845.40	830.80	821.28	787.68	831.15
W#3 Apr 2024	846.94	922.85	1085.75	1156.31	1188.67	1091.37	1343.85
W#4 Apr 2024	2054.09	2655.84	2378.47	2598.04	2549.67	1983.05	1960.37

Fig 8. Day to day building energy consumption profile

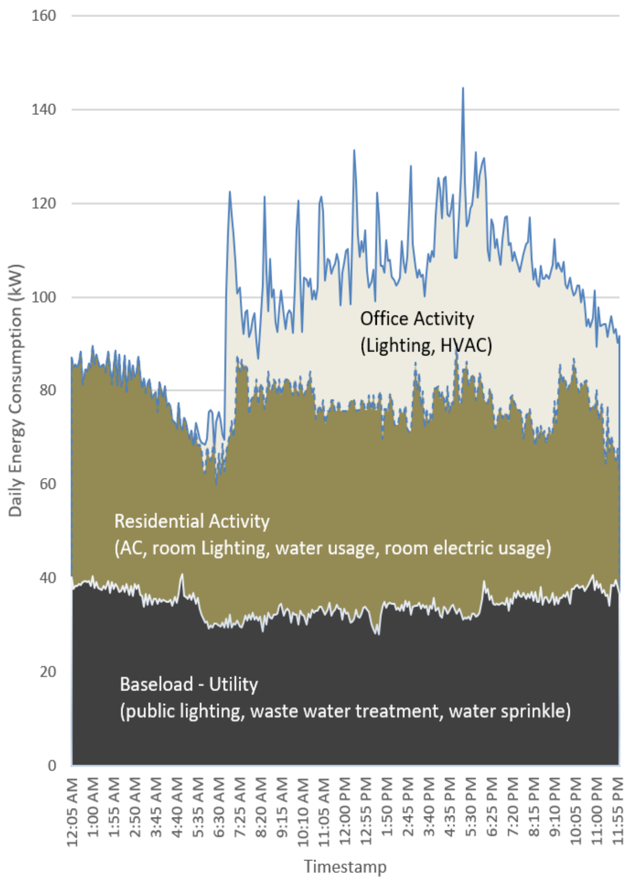


Fig 9. One day energy profile in peak and low condition

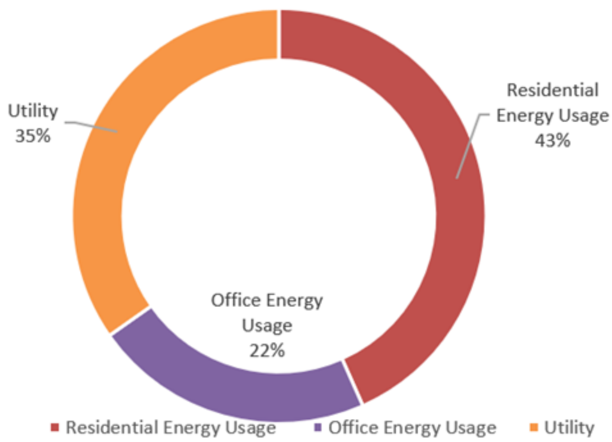


Fig 10. Building Energy Consumption Profile

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