A COMPREHENSIVE METHODOLOGY FOR MONITORING AND ANALYSING ENERGY CONSUMPTION IN PUBLIC FACILITIES: CASE STUDY OF A PUBLIC FACILITY

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ABSTRACT

This study conducted an energy efficiency assessment of a public facility, analysing various electrical parameters including line and phase voltages, current, real and apparent powers, and power factor. The analysis reveals significant imbalances across phases, highlighting inefficiencies that contribute to potential safety concerns, equipment stress and reduced equipment lifespan. The key findings include maximum phase voltages which exceeds acceptable limits by up to 15%, while the minimum line voltages fall below recommended ranges by 10%. One phase carries 2.4 times the current of another. One phase consumed 130% more real power than another as the apparent power distribution mirrors real power, with one phase exhibiting a 140% higher maximum value than another. The measured power factors ranged from 0.42 - 0.99 across phases, indicating potential for improvement, while the current unbalanced factor of 44.2% is high and indicates a serious current imbalance.. Addressing these imbalances and inefficiencies present significant opportunities for improvement. Optimizing power systems through load balancing, reactive power compensation, and efficient equipment use enhances safety, extends equipment life, and boosts sustainability. This study emphasizes the importance of detailed power analysis for optimizing energy use and promoting sustainability in public facilities. By addressing the identified issues, the facility can pave the way for a more energy efficient system.

Key words: Power factor, energy efficiency, power distribution

Introduction

The escalating urgency of addressing climate change (Atwoli, 2022), coupled with rising energy costs (Hussain, 2024) and increasing societal demands for public services, necessitates a paradigm shift towards enhanced energy efficiency in public facilities (Umoh *et al*., 2024). These facilities, spanning across diverse functionalities, often consume substantial energy, presenting opportunities for significant and impactful interventions. This study examines the energy consumption and energy efficiency in a public facility. The study utilizes a case study approach to illustrate the potential benefits and implications of energy efficient facilities. Public facilities frequently grapple with tight financial budgets and rising energy costs (Abdelaziz, 2024). Implementing targeted energy efficiency measures not only translates to substantial financial savings but also contributes to environmental sustainability. Reduced energy consumption lowers greenhouse gas emissions, mitigates climate change impacts, and aligns with national and international sustainability goals. By pursuing energy efficiency goals, public facilities not only benefit from their own operations, but also inspire broader societal adoption of sustainable practices. Additionally, the data generated through energy monitoring can inform national energy policies, shaping regulatory frameworks and driving wider systemic change.

Detailed energy usage analysis often reveals hidden inefficiencies within buildings and equipment. Addressing these inefficiencies translates to improved thermal comfort, enhanced lighting systems, and better overall functionality within the facility. Additionally, efficient equipment utilizes less energy, leading to reduced maintenance costs and extended equipment lifespans (Yazdi, 2024). Public engagement with energy consumption data fosters transparency and understanding regarding the environmental and financial impacts of energy use lifespans. This empowers individuals to adopt more sustainable practices within their own lives, contributing to a broader cultural shift towards responsible resource management (Dushkova, D., & Ivlieva, O. 2024). By sharing their success stories and methodologies, public facilities can function as collaborative hubs for energy efficiency within the sector. This collaborative approach could facilitate the diffusion of best practices, accelerating the adoption of effective solutions across diverse types of public facilities.

This study delves into the practical implementation of energy monitoring in a public facility. It leverages data from a 10-day monitoring period conducted with a Power Quality Analyzer to evaluate its energy use and identifies the potential areas for improvement. By highlighting operational enhancements and the potential for public engagement and knowledge sharing, this research aims to contribute to a growing body of knowledge on optimizing energy consumption within public settings. The findings generated will hold vital implications for policymakers, facility managers, and the general public, ultimately contributing to a more sustainable and resource-efficient future. Indeed, studying energy consumption and efficiency in public facilities is crucial for several reasons. Firstly, it offers significant financial savings by reducing energy costs, freeing up resources for other essential services (Tian, 2024). Secondly, it minimizes environmental impact through lower greenhouse gas emissions, contributing to sustainability goals. Additionally, it highlights leadership and can inform policy by demonstrating best practices and informing local and national regulations. Finally, public engagement with energy data fosters awareness and inspires responsible resource management within the community.

Location of Study

This study was undertaken at a research institution located in East Legon, Accra, a suburb characterized by modern infrastructure and a vibrant commercial sector within Ghana's capital city (see Figure 1-1). Accra. Accra experiences a tropical savanna climate characterized by a wet and dry seasons. The study area falls within this climatic zone, typically experiencing a rainy season from April to July and a dry season from November to March. Accra's climate is characterized by high temperatures throughout the year, with average daily temperatures ranging from 24°C to 32°C. Daily temperature ranges are generally moderate. Sunshine hours are abundant during the dry season. Relative humidity is typically high, especially during the rainy season, often exceeding 80%. Atmospheric pressure generally varies slightly throughout the year, with lower pressure associated with the rainy season and higher pressure during the dry season (World Bank, 2025). However, rainfall patterns in Accra have shown increasing variability in recent years, with occurrences of both more intense rainfall events and prolonged dry spells. These climatic variations, including changes in temperature, rainfall patterns, sunshine hours, humidity, and atmospheric pressure, present challenges and opportunities for research and development in the region.

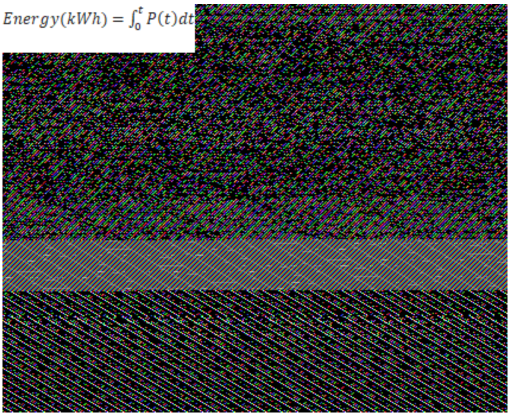

Fig. 1-1: Study site, East Legon-Accra, Source (Google Earth, 2025)

About the Institute

The Institute is renowned for its expertise in a diverse range of fields, including sanitation and environmental management, sustainable energy technologies, materials science, manufacturing and engineering design and prototyping. This expertise is supported by strong capabilities in metrology, ensuring accurate measurements, and a business development function that facilitates technology transfer and commercialization. The institute also a strong emphasis on human resource development, fostering a skilled workforce and creating an enabling environment for research and innovation. The institution provides access to research facilities, including scientific laboratories, pilot plants, analytical instruments and mechanical engineering workshop. This research environment was chosen due to its strong emphasis on applied research, aligning perfectly with the study's objective to develop a practical solution and inform policy decisions and business owners.

The institution comprises several buildings such as an administrative block housing key departments (Director's office, Human Resources, Accounts, Registry, Conference Room), a research block with workshops (Mechanical, Carpentry), and a Metrology Division block with specialized calibration laboratories (electricity, temperature, pressure, mass, sound). A block is dedicated to materials science and manufacturing, including a glass-blowing workshop and a chemistry laboratory. This infrastructure provides a strong foundation for research and development activities within the institution. The equipment that uses electricity include mainly laboratory equipment and machinery, mechanical workshop tools such as welding and cutting machines, air conditions, ceiling fans, laptops and desktop computers used by staff. Most of the lights used in the facility are LED lights for both inside and outside the buildings.

The human capacity of employees includes researchers at various levels, from Research Scientists to Principal Research Scientists, as well as technical staff such as Chief Technologists, Assistant Research Scientist, and Technicians. Administrative personnel include a Director, Senior Administrative Officers, and other support staff such as accountants, marketing officers, and human resources personnel. This diverse workforce plays a crucial role in supporting the research and development activities of the institution with a total staff population of 114 with about 46% being females (Institute's Annual Report, 2021).

Literature Review: Energy Efficiency Monitoring Techniques

Global energy demand, coupled with climate change and resource depletion concerns, necessitates improved energy efficiency (IEA, 2023). This need for improved energy efficiency is directly linked to the goal of reducing energy consumption while maintaining service levels (Domínguez, *et al*., 2025), a crucial step towards a sustainable energy future (UN, 2024). Achieving this reduction in energy consumption, through minimizing energy waste and optimizing use, offers multiple benefits, including reduced emissions (Liu, H. *et al*., 2025), and enhanced energy security (Liu, H. *et al*., 2025). A foundational element for any successful energy efficiency strategy, and thus for realizing these benefits, is effective energy consumption monitoring (Emon, M. *et al*., 2025). This monitoring provides the vital data and insights necessary to identify areas for improvement in energy use, track progress in implementing energy-saving measures, and evaluate the overall effectiveness of those measures (Ebirim, *et al*., 2024). Therefore, this review, focusing on the critical role of energy consumption monitoring in successful energy efficiency strategies, will explore various energy efficiency monitoring techniques and technologies, highlighting their applications in achieving these goals.

Energy Audits and Assessments: Energy audits are the foundational step in understanding and improving energy efficiency (ASHRAE, 2018). They involve a systematic inspection and analysis of energy flows within a building, process, or system. The primary goal is to identify areas of energy waste, inefficiencies, and opportunities for improvement. Audits can range in scope and complexity. A basic walk-through audit might involve a visual inspection and simple calculations to identify obvious energy losses. More detailed audits, often called investment-grade audits, involve extensive data collection, detailed engineering analysis, and cost-benefit analysis of potential energy-saving measures. Standards like those from ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) classify audits into different levels (e.g., Level I, II, III) based on their depth and comprehensiveness (ASHRAE, 2011). ISO 50002 provides an international standard for conducting energy audits, outlining requirements for planning, data collection, analysis, and reporting, ensuring a consistent and structured approach (ISO, 2014).

Smart Meters and Advanced Metering Infrastructure (AMI): Smart meters represent a significant step towards improving energy management and efficiency within modern energy systems (Roy, & Sarker 2024). Unlike traditional meters that only measure total energy consumption, smart meters can measure and communicate energy usage data in near real-time. This data provides valuable insights into consumption patterns, allowing users to identify peak demand periods, understand how energy is being used, and implement targeted energy-saving strategies. AMI goes beyond just the smart meters themselves; it encompasses the entire system of smart meters, communication networks (often using wireless technologies), and data management systems. The two-way communication capabilities of AMI are particularly important. They enable utilities to communicate with consumers about energy usage, offer demand response programs, and implement dynamic pricing based on real-time grid conditions (Gellings, 2024). For consumers, AMI data can be accessed through online portals or mobile apps, providing personalized energy usage information and recommendations.

Building Energy Management Systems (BEMS): Building Energy Management Systems (BEMS) are control systems designed to monitor and manage energy consumption in buildings. They act as the central nervous system for building energy efficiency (Chatzikonstantinidis, K. *et al*., 2025), integrating and controlling various building systems, such as HVAC (heating, ventilation, and air conditioning), lighting, appliances, and other energy-consuming equipment (Wang, Y., *et al*. 2024). BEMS use sensors and controllers to collect data on building conditions (temperature, occupancy, lighting levels) and automatically adjust building systems to optimize energy use. For example, a BEMS can adjust HVAC schedules based on occupancy patterns, dim lights when daylight is available and shut down equipment during unoccupied periods. Furthermore, BEMS collect and analyse energy data, providing valuable insights into building performance, identifying areas for improvement, and generating reports on energy consumption. Modern BEMS often incorporate cloud connectivity and data analytics capabilities, enabling remote monitoring and advanced analysis.

Internet of Things (IoT) and Wireless Sensor Networks (WSN): The Internet of Things (IoT) and Wireless Sensor Networks (WSN) are revolutionizing energy monitoring by enabling the deployment of numerous interconnected sensors to collect energy-related data from a wide range of sources (Khalaf & Abdulsahib, 2025). These sensors can be embedded in appliances, lighting fixtures, HVAC systems, and other equipment, providing data on energy consumption at the individual device or appliance level (Sayed, *et al*., 2025). This level of detail allows for a much deeper understanding of energy usage patterns and identification of specific energy waste. WSNs typically consist of a network of low-power, wireless sensors that communicate with a central data collection point. IoT-enabled devices can be accessed and controlled remotely, allowing for real-time monitoring, adjustments, and optimization of energy consumption (Kalambe, S. *et al*., 2025). The data collected by IoT sensors can be used to create detailed energy profiles, identify anomalies, and inform energy-saving strategies (Oluokun, *et al*., 2025).

Data Analytics and Machine Learning: The vast amounts of data generated by smart meters, BEMS, IoT sensors, and other monitoring technologies require sophisticated tools for analysis. Data analytics and machine learning techniques are increasingly used to process this data and extract valuable insights for energy efficiency (Veeramachaneni, V. 2025). Machine learning algorithms can be trained on historical energy data to predict future energy consumption based on various factors, such as weather patterns, occupancy schedules, and equipment usage (Sayed, *et al*., 2025). This predictive capability allows for proactive energy management, enabling adjustments to building systems or operations to minimize energy costs. Data analytics can also be used to detect anomalies in energy consumption patterns, which may indicate equipment malfunctions, energy waste, or other issues. Identifying these anomalies early can result in corrective actions taken to improve energy efficiency.

Non-Intrusive Load Monitoring (NILM): Non-Intrusive Load Monitoring (NILM) is a clever technique that uses a single energy meter to disaggregate the energy consumption of individual appliances within a building (Liu, *et al*., 2024). Instead of installing separate meters for each appliance, NILM algorithms analyse the subtle changes in the overall energy consumption signal to identify the operating patterns of different appliances. This approach is cost-effective because it eliminates the need for extensive metering infrastructure. NILM can provide detailed information on appliance-level energy usage, allowing users to understand which appliances are consuming the most energy and identify opportunities for improvement. For example, NILM can identify appliances that are left on unnecessarily or operating inefficiently. While NILM has made significant progress, its accuracy can be affected by factors such as the complexity of the electrical system and the similarity of operating patterns between different appliances.

Emerging Technologies: The field of energy efficiency monitoring is constantly evolving with the emergence of new technologies. Artificial intelligence (AI) is playing an increasingly important role, with AI-powered systems automating energy optimization tasks, learning from data, and continuously improving energy efficiency (Jalasri, M., 2025). Digital twins, which are virtual replicas of physical systems, can be used to simulate and optimize energy performance before implementation, reducing the risk and cost of real-world experiments (Lemian, D., 2025). Blockchain technology has the potential to enable secure and transparent energy data sharing, facilitating peer-to-peer energy trading and more efficient grid management (Babaei, A., 2025). These emerging technologies hold great promise for further advancements in energy efficiency monitoring and optimization. There are opportunities for best practices of energy efficiency in buildings.

Best Practices of Energy Efficiency in Buildings

Achieving optimal energy efficiency in buildings requires a comprehensive and integrated approach, encompassing all stages of a building's lifecycle. From the initial design phase, prioritizing building orientation and envelope optimization is crucial. Maximizing natural daylight and minimizing solar heat gain through strategic window placement and shading devices significantly reduces energy demands (ASHRAE, 2018). A well-insulated building envelope, constructed with high-performance windows and sustainable materials, further minimizes heat transfer, leading to lower heating and cooling loads. Passive solar design principles, such as utilizing thermal mass can effectively harness natural energy sources. During construction, proper commissioning of building systems (HVAC, lighting, controls) is essential to ensure they operate efficiently from the start (ASHRAE, 2011). Furthermore, incorporating energy-efficient appliances (Energy Star certified) and implementing smart plugs to eliminate phantom loads contribute to overall energy reduction. Effective building management, including regular energy audits (ISO, 2014) and the use of Building Energy Management Systems (BEMS), allows for continuous monitoring, control, and optimization of building systems (Digitemie & Ekemezie 2024). Beyond design and construction, ongoing operational practices play a vital role in maintaining and improving energy efficiency. Regular maintenance of HVAC systems, including filter changes and coil cleaning, ensures optimal performance (Gellings, 2024). Implementing lighting controls, such as occupancy sensors and daylight dimming, minimizes unnecessary energy consumption. Engaging occupants in energy-saving practices and analysing energy data to inform targeted strategies are crucial for sustained efficiency gains. Retro-commissioning, periodically re-evaluating building systems, helps ensure they continue to operate effectively over time. Integrating renewable energy sources, like solar panels, and implementing water conservation measures, such as low-flow fixtures and rainwater harvesting, further enhance building sustainability (IEA, 2023; UN, 2024). A critical component of effective building operation and energy management is the ability to accurately monitor and analyse power system performance in real-time.

Occupancy sensors detect the presence of occupants in a space and automatically adjust lighting, HVAC, and other systems accordingly. This technology can significantly reduce energy waste in unoccupied or underutilized areas of a building. Research indicates that occupancy sensors can significantly reduce energy consumption, especially in areas with inconsistent usage like offices, conference rooms, and restrooms, as they automatically turn off lights when a space is unoccupied, leading to substantial energy savings. (Pang, *et al*. 2024). Advanced occupancy sensing systems can even learn occupant behaviour patterns and optimize building controls proactively.

Real-Time and Cumulative Power System Parameter Calculations

The analysis of power system performance relies on accurate calculations of various parameters, performed in real-time by installed equipment. In this study PowerTrack energy monitor was used. This PowerTrack monitor utilizes embedded formulas to determine both real-time and cumulative data for key metrics. These metrics include active power, reactive power, apparent power, power factor, voltage and current harmonics, and energy consumption. The embedded equations account for both single-phase and three-phase systems. The equipment also calculates harmonic distortion using established methods. This direct calculation by the installed equipment ensures accurate and immediate insight into the power system's performance. To illustrate the principles behind these calculated values, the following equations are provided.

Active Power (P) (kW): The fundamental relationship for calculating active power (P) in a single-phase AC system is based on the concept of instantaneous power. At any given instant (t), the instantaneous power (p(t)) is the product of instantaneous voltage (v(t)) and instantaneous current (i(t)). However, for practical applications, we are usually more interested in the average power over complete cycle of a waveform. The average active power (P) over a complete cycle of the AC waveform can be expressed as the integral of the instantaneous power. Equation 1 is the most valid and general definition of average power. It is true for any voltage and current waveform, whether it is sinusoidal, square, triangular, or any other shape. It is the fundamental way to calculate average power. Many modern electrical loads (like computers, LED lighting, variable speed drives) draw currents that are not sinusoidal (Saleem, R, 2025). In these cases, Equation 1 becomes most suitable to use to calculate the average power.

$$P = \frac{1}{T}\int_0^t v(t) * i(t)dt \quad \text{Equation 1}$$

where T is the period of the AC waveform ($T = {}^1/_f$, f being the frequency).

For a purely sinusoidal voltage and current waveforms, this integral simplifies to a more common used form:

$$P = IVCcos(\varphi) \quad \text{Equation 2}$$

where V and I are the RMS voltage and current, respectively, and φ is the phase angle between the voltage and current waveforms.

Equation 2 is a special case of Equation 1 and Equation 1 is only valid when the voltage and current waveforms are perfectly sinusoidal. This can be applied to single-phase systems with appropriate adjustments for voltage measurement (line voltage for phase-to-phase). For three-phase balanced systems, the total active power can be calculated by summing the active power of each phase:

$$P_{total} = P_{phase\ 1} + P_{phase\ 2} + P_{phase\ 3} \quad \text{Equation 3}$$

Alternatively, for three-phase systems with balanced or unbalanced loads, the following equation can be used:

$$P_{total} = \sqrt{3}V_{line} * I_{line} * Cos(\varphi_{line}) \quad \text{Equation 4}$$

where V_{line} and I_{line} are the RMS line voltage and line current, respectively, and φ_{line} is the phase angle between the line voltage and line current.

Reactive Power (Q) (kVAr): Similar to active power, reactive power (Q) represents the exchange of reactive energy between the source and the load. The calculation follows the same principle as active power but using the sine function of the phase angle (sin(φ)) instead of the cosine function (cos(φ)).

$$Q = VI * Sin(\varphi) \quad \text{Equation 5}$$

Apparent Power (S) (kVA): Apparent power (S) represents the total volt-ampere (VA) rating of an AC circuit and is calculated as the product of RMS voltage and current.

$$S=VI \quad \text{Equation 6}$$

Power Factor (PF): The power factor (PF) is a dimensionless quantity that reflects how efficiently electrical power is being used. It is the ratio of active power (P) to apparent power (S).

$$PF = Cos(\varphi) = \frac{P}{S} \quad \text{Equation 7}$$

Energy Consumption (kWh): This represents the total amount of electrical energy consumed over a specific period (t). It is calculated by integrating the active power (P(t)) over that time period.

$$Energy(kWh) = \int_0^t P(t)dt \quad \text{Equation 8}$$

The integration can be performed numerically using metering devices that record power data at regular intervals. Maximum Demand (kVA).

This is the highest value of apparent power recorded over a specific period

Harmonics in Non-linear Waveforms

Harmonics, unwanted multiples of the fundamental power frequency, are a growing problem in modern power systems. Generated by non-linear loads (like electronics and variable speed drives), they distort voltage and current waveforms (Subramanian & Alexander, 2024). This distortion leads to several key issues: inaccurate power calculations, increased equipment heating, voltage distortion (including flickering lights), broader power quality problems (like voltage sags and swells), and resonance. These issues can cause equipment damage, reduced efficiency, and interference, making understanding and mitigating harmonics crucial for reliable power system operation (Ali, *et a*l., 2024). Installing power quality monitors allows for continuous monitoring of harmonic levels. This helps to detect changes and ensure that mitigation measures are working effectively.

Power analysers are essential tools for determining harmonic distortion in electrical systems. The power analyser uses the FFT algorithm to decompose the digital waveform into its constituent frequency components. It essentially breaks down the complex waveform into a sum of sine waves at different frequencies, revealing the fundamental frequency and the harmonics, a measure of the overall distortion of the waveform. It is calculated as the ratio of the RMS value of all harmonic components to the RMS value of the fundamental component. Power analysers use sophisticated digital signal processing techniques, primarily the FFT algorithm, to analyse voltage and current waveforms and determine the presence and magnitude of harmonics. They provide valuable information for understanding and mitigating harmonic distortion in power systems.

Mitigating harmonics in power systems requires a multi-pronged approach. Filtering solutions, both passive and active, are commonly employed. Passive filters block specific harmonic frequencies, while active filters inject cancelling currents, offering greater adaptability but increased complexity and cost. Equipment modifications, such as using low-harmonic drives and K-rated transformers, reduce harmonic generation at the source and enhance equipment resilience. System design and operational practices, including load balancing, minimizing cable lengths, and proper grounding, also contribute to harmonic reduction. Advanced techniques like harmonic cancellation and active harmonic conditioning offer further options. Crucially, continuous monitoring and analysis through harmonic studies and power quality monitoring ensure effective harmonic management. The optimal solution depends on specific system needs, cost, and complexity. Collaborative approaches, especially in shared grid scenarios, often prove most effective.

Data Collection Equipment

In the pursuit of understanding, data collection acts as the cornerstone, meticulously gathering information to illuminate hidden truths. While the act itself transcends specific tools, equipment often serves as the bridge between our curiosity and the world's secrets. The instrument used in this study was the Power Track Energy Analyzer and Verifier v3.2.1. The Power Track Energy Analyzer and Verifier is a portable device used to monitor and analyse electrical parameters like voltage, current, power, and power factor at a specific electrical supply point. It records data, which can be analysed using software to gain insights into energy consumption patterns, identify potential efficiency issues, and verify billing accuracy. The power track energy analyser has an onboard flash memory with presets for recording intervals ranging from 1 second to 60 minutes.

Experimental

Equipment Installation and Configuration

The PowerTrack (Figure 3-1) device was installed at the service panel, the point of entry for incoming electricity from the utility company, where it is then distributed to various circuits powering lights, outlets, and appliances within the research institution. Split-core current transformers were carefully connected around each of the three phase conductors of the circuit under investigation. Proper polarity was ensured by observing the current transformer's markings and ensuring the correct orientation relative to the direction of current flow. The voltage probes were connected to each phase conductor and the neutral line. The PowerTrack unit was powered on and configured using the device's built-in interface and was configured to record the Active power (kW), Reactive power (kVAr), Apparent power (kVA), and power factor The data sampling rate was set to 1-second intervals to capture power system dynamics accurately.

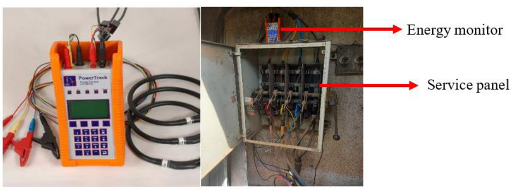

Fig. 3-1: The Power track energy analyser and verifier installed at study site

Data Collection

Data was collected over a period of 10 days, using a PowerTrack device from October 30th to November 8th, 2021. The 10-day monitoring period was selected to capture a representative sample of the facility's typical energy consumption patterns. The institute's primary operations occur during weekdays, from 8:00 am to 5:00 pm, with minimal activity on weekends. This 10-day period included eight weekdays and two weekend days, allowing us to assess energy usage during both operational and non-operational periods. While weekend activity is generally low, it is not entirely absent, as occasional projects or lab work may extend into the weekend. The inclusion of weekend data, even if representing lower usage, provides a more complete picture of the facility's overall energy profile. Furthermore, the consistent nature of the institute's general activities throughout the year suggests that the energy consumption patterns observed during this 10-day period are likely representative of typical usage throughout the year. This timeframe allowed for the collection of sufficient data to identify key energy consumption trends and potential areas for improvement, while also being a practically manageable duration for data collection within the project's resources. The duration of data collection plays a crucial role in painting a complete picture of energy consumption within the public facility. While the existing 10-day dataset offers a valuable snapshot, the study's limitation included inability of stretching the monitoring period further. This expanded period would have allowed to capture seasonal variations in energy use, accounting for fluctuations in weather, occupancy, and operational schedules. Additionally, extending the monitoring could reveal cyclical patterns or infrequent high-demand events that might be missed in a shorter period. Longer is not always better, hence a carefully evaluated resources available were employed and it was ensured that the chosen duration aligned with the research objectives.

Upon completion of the recording period, the device was connected via USB cable to an 11th Gen Intel(R) Core(TM) i7-1165G7 processor (2.80GHz, 4 cores, 8 threads). The recorded data was then downloaded from the device using the manufacturer-supplied software PowerTrack Data Analyzer v3.2.1. The data was downloaded from the PowerTrack device by connecting it to the computer via the provided USB cable. The PowerTrack Data Analyzer software was then launched, and the 'Download Data' function was selected. The software automatically detected the connected device and prompted for the destination folder for the downloaded data. The 'Download All Data' option was selected to ensure all recorded data was downloaded.

The key electrical parameters measured included, record real-time and cumulative data for: active power (kW), reactive power (kVA_r), demand power (kVA), power factor, voltage harmonics, and current harmonics. The active power (kW) measures the actual energy used for work, while reactive power (kVA_r) influences efficiency without performing work itself . By monitoring these one gains insight into overall energy consumption and potential power factor improvement opportunities. The demand power, measured in kVA, reveals the facility's maximum instantaneous power draw, providing crucial information for peak demand management and potential cost reductions. Power Factor, which is a vital efficiency indicator, signifies how effectively active power is utilized. By monitoring it one can identify areas for improvement and potentially reduce reactive power, leading to energy cost savings. The voltage and current harmonics, often caused by electronic devices, can create distortions and inefficiencies. Measuring them helps assess power quality and identify potential equipment issues or compatibility concerns. Current harmonics increase power losses and cause overheating and other issues. Voltage harmonics affect the performance of sensitive equipment.

Data Analysis and Energy Efficiency Assessment

The analysed data was exported from the PowerTrack Data Analyzer software in CSV format for further analysis and visualization in MS Excel. Delving into the captured data unveils its secrets through advanced analytical techniques. Descriptive statistics lay the groundwork, painting a picture of central tendencies, variability, and outliers. Time series analysis then takes center stage, revealing periodic patterns in energy consumption, uncovering hidden periodicities and their potential drivers. Further dissection occurs with demand profile analysis, pinpointing peak demand intervals and their contributing factors like weather or occupancy. Power factor analysis examines its impact on efficiency and potential cost savings, while also evaluating harmonic distortions and mitigation strategies. Finally, correlation analysis steps in, uncovering hidden relationships between energy use and influencing factors like operational schedules, revealing a more holistic understanding of the facility's energy dynamics.

Evaluating a facility's energy efficiency requires delving beyond raw data. Building upon the insights gleaned from analysis, several key assessments pave the way for targeted improvements. No system is perfectly efficient, and quantifying energy losses throughout the facility unveils hidden inefficiencies. Transmission losses, distribution losses, and inefficient equipment operation each contribute to the overall energy bill. By understanding the magnitude and location of these losses, targeted interventions can be prioritized, maximizing both cost savings and environmental benefits.

Results

Phase Voltage

Figure 4-1 shows the voltage distribution in the institution, where the study took place. The recorded maximum phase voltages (MaxVa = 255V, MaxVb = 253V, MaxVc = 254V) indicate slight imbalances. To quantify this, we calculate the Voltage Unbalance Factor (VUF):

$$Average\ voltage = \left(\frac{255+253+254}{3}\right) = 254V \quad \text{Equation 9}$$

$$Max\ deviation = 255 - 254 = 1V \quad \text{Equation 10}$$

$$VUF = \left(\frac{1}{254}\right)x100\% = 0.39\% \quad \text{Equation 11}$$

This VUF of 0.39% is well within the acceptable limit of typically 2%, suggesting a relatively balanced voltage supply. However, the average phase voltages (Avg Va = 238 V, Avg Vb = 236 V, AvgVc = 237 V) are lower, indicating potential voltage drops.

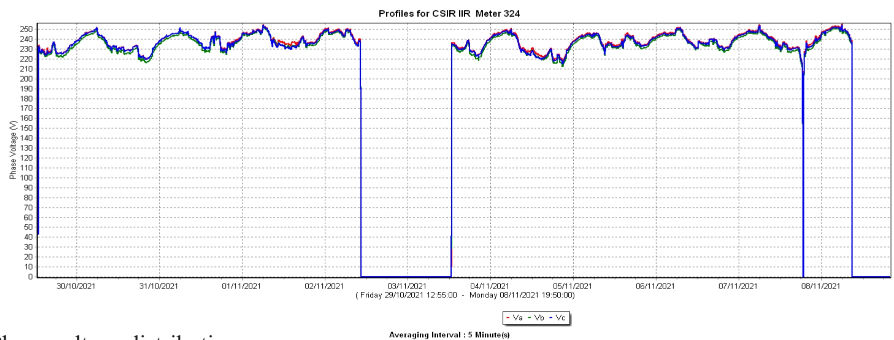

Figure 4-1: Phase voltage distribution

Line Voltage

The maximum line voltages (Max Vab = 440 V, Max Vbc = 439 V, Max Vca = 441 V) also show slight imbalances (Figure 4-2).

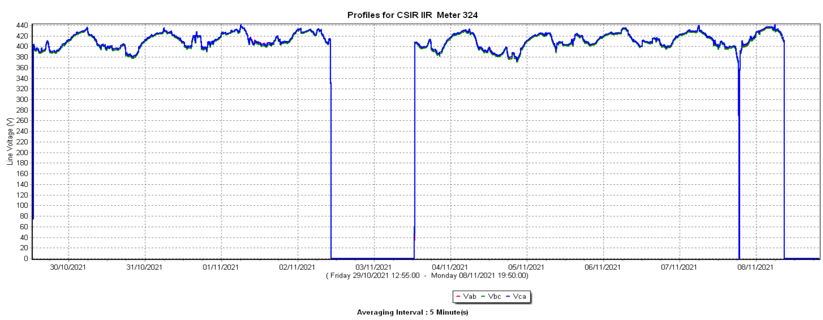

Fig. 4-2: Line voltage distribution

$$Average\ power = \left(\frac{440+439+441)}{3}\right) = 440 \qquad \text{Equation 12}$$

$$Max\ deviation = 441 - 440 - 1V \qquad \text{Equation 13}$$

$$VUF = \left(\frac{1}{440}\right) X100\% = 0.23\% \qquad \text{Equation 14}$$

This VUF of 0.23% is also well within acceptable limits. However, the minimum line voltages (Min Vab = 270 V, Min Vbc = 269 V, Min Vca = 272 V) show significant voltage drops, which need to be investigated. The average line voltages (Avg Vab = 238 V, Avg Vbc = 236 V, Avg Vca = 237 V) are consistent with the average phase voltages, reinforcing the need to address the voltage drop issue.

Electrical Current

Figure 4-3 represents the three-phased system electric current. The maximum phase currents (Max Ia = 30.4 A, Max Ib = 46.2 A, Max Ic = 70.9 A) show significant imbalance. Following a similar calculations in equation 12 to equation to 14 the current unbalance factor (CUF) is calculated as 44.2%, which is extremely high and indicates a serious current imbalance. This imbalance is likely contributing to the observed voltage imbalances and needs immediate attention.

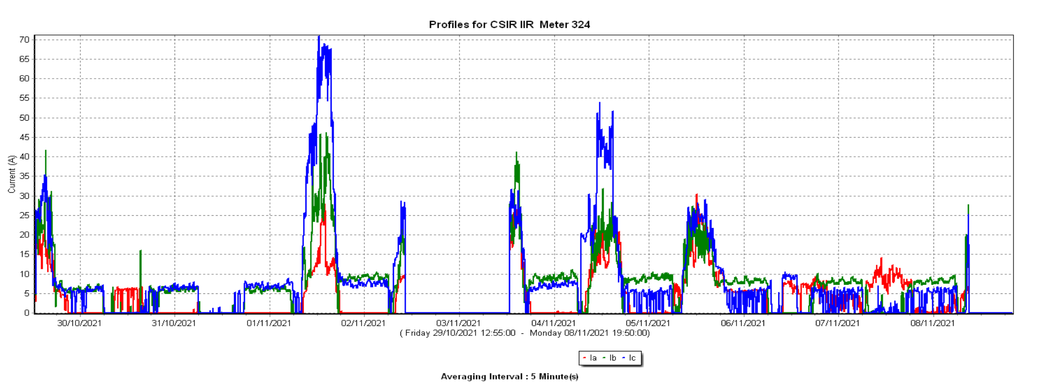

Fig. 4-3: Three-phased system electric current

Real Power Distribution

Figure 4-4 shows the real power distribution across phases depicting a significantly unbalanced. Phase C (15.732 kW) consumes considerably more than Phase A (6.368 kW) and Phase B (10.110 kW). This uneven distribution leads to inefficiencies and potential losses. The percentage difference between the highest and lowest phase power is:

$$Power\ difference = \left(\frac{15.732-6.367}{15.732}\right) X100\% = 59.8\% \qquad \text{Equation 15}$$

This large power difference necessitates investigation into the loads connected to each phase.

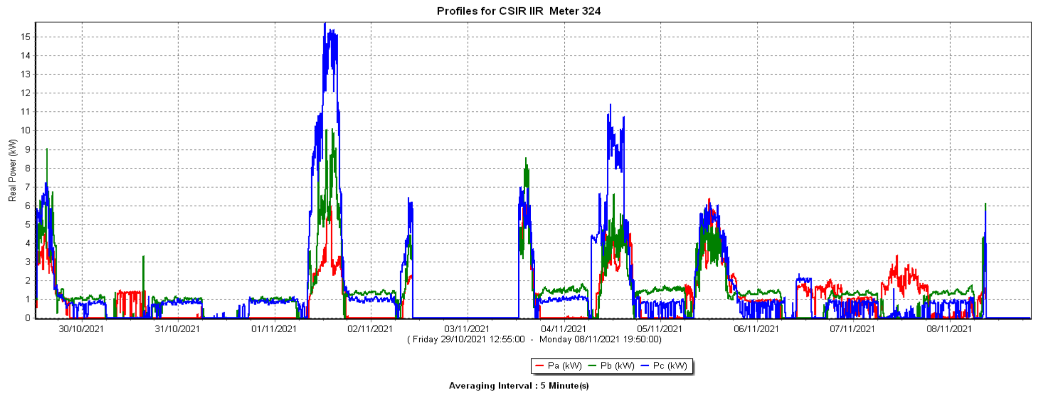

Fig. 4-4: Real power distribution across phases

Reactive Power

The reactive power values (Phase A: 3.390 kVAr, Phase B: 3.717 kVAr, Phase C: 4.378 kVAr) also show some imbalance, but the magnitudes are relatively low compared to the real power (Figure 4-5).

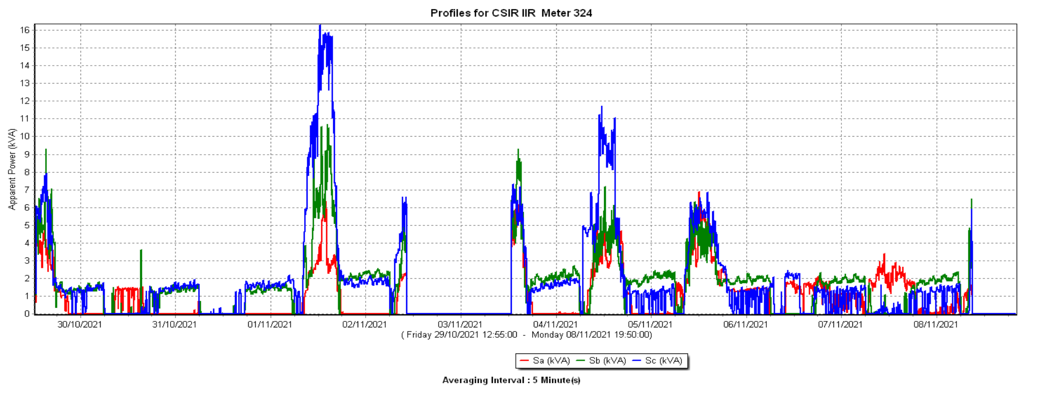

Fig. 4-5: Reactive power in capacitive or inductive load

Apparent Power Distribution

Figure 4-6 shows the apparent power distribution, which mirrors the real power distribution, with Phase C (16.292 kVA) drawing significantly more than Phase A (6.876 kVA) and Phase B (10.694 kVA). Similar to the real power analysis, significant differences exist between phases, with Phase C exhibiting the highest apparent power demand, nearly 2.4 times greater than Phase A. This reflects both real power imbalances and potential variations in reactive power contribution across phases. Compared to real power values, apparent power values are naturally higher due to the inclusion of the reactive power. This highlights the additional burden placed on the supply due to inefficiencies associated with reactive power. Uneven apparent power distribution across phases presents opportunities for targeted demand management strategies. Focusing on Phase C, through load balancing, optimizing equipment operation, or implementing demand response programs, can significantly reduce peak demand and potentially lower energy costs.

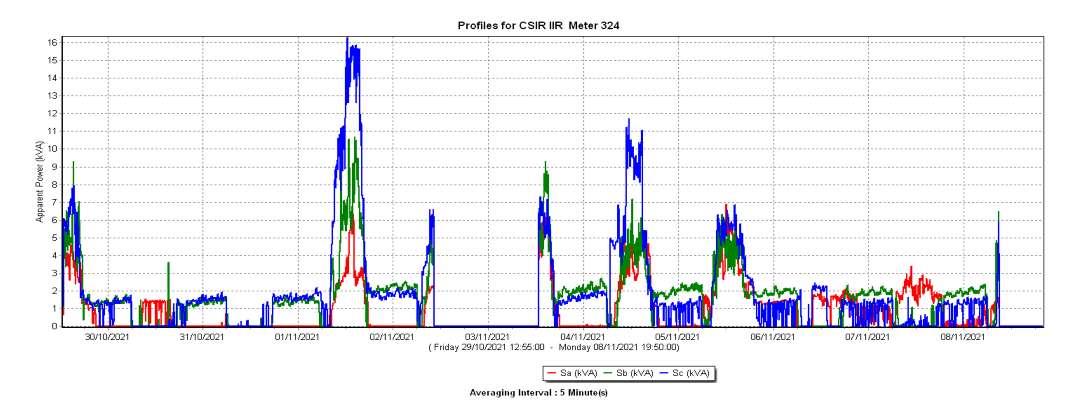

Fig. 4-6: Apparent power distribution across phases

Power Factor Variation

As shown in Figure 4-7, The facility's electrical system experiences a wide range of power factors (0.42 - 0.99), signifying a fluctuating balance between working power (kW) and apparent power (kVA) demand. This variation in power factor, also known as the system's "demand profile," reflects changes in operational activities and their impact on current draw.

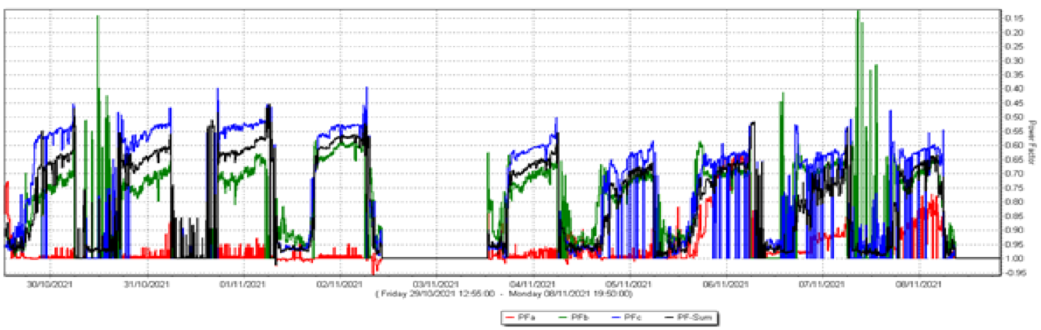

Fig. 4-7: Power factor variation

Discussion

The analysis of the electrical system data reveals several key issues that warrant further investigation and potential corrective actions.

Voltage Imbalance: While the calculated Voltage Unbalance Factor (VUF) for both phase and line voltages is within acceptable limits (<2%), the observed average voltages are lower than the nominal voltage, indicating a potential voltage drop issue. This suggests that while the relative difference between phases is small, the overall voltage level is depressed. This could be due to factors like long cable runs, high loading, or issues with the supply transformer. The minimum line voltages dipping significantly (down to 270V) further reinforces the voltage drop concern and could negatively impact the performance and lifespan of connected equipment.

Current Imbalance: The most alarming finding is the extremely high Current Unbalance Factor (CUF) of 44.2%. This is far beyond acceptable limits and indicates a serious problem. Such a high imbalance can lead to overheating of transformers and conductors, increased losses, and reduced equipment lifespan. The significant difference in current draw between phases (70.9A on Phase C compared to 30.4A on Phase A) strongly suggests uneven loading across the phases. This should be immediately investigated and addressed by redistributing loads to achieve a more balanced current draw.

Power Imbalance: The analysis of real and apparent power distribution further highlights the severe load imbalance. Phase C consumes significantly more power (both real and apparent) than the other two phases. The 59.8% difference between the highest and lowest phase power is substantial and directly contributes to the current imbalance. This uneven power distribution can lead to inefficiencies in the system and increased costs. A detailed audit of the loads connected to each phase is crucial to identify the sources of this imbalance and implement corrective measures.

Reactive Power: While the reactive power values show some imbalance, their magnitude is relatively low compared to the real power. This suggests that the power factor, while fluctuating, is generally not excessively poor. However, the wide range of power factor (0.42-0.99) indicates that there are periods of significant reactive power demand. This variability can impact the overall system efficiency and may warrant further investigation into the types of loads connected and their operating cycles. Installing power factor correction equipment, such as capacitors, could be considered to improve the power factor and reduce losses.

Overall System Performance: The combined effects of voltage drop, current imbalance, and power imbalance are likely contributing to increased losses, reduced efficiency, and potential equipment stress within the electrical system. Addressing the current and power imbalances should be prioritized, as these are the most significant issues identified. Once these are addressed, the voltage drop issue can be further investigated.

Limitations of the Study: This study is based on a limited monitoring period. A longer monitoring period, covering different operational cycles and seasons, would provide a more comprehensive understanding of the system's behavior and identify any seasonal variations in loading and power demand. Additionally, the study does not provide details about the specific loads connected to each phase. A detailed load audit is essential for effectively addressing the identified imbalances. Finally, the study does not explicitly consider the potential impact of the observed imbalances on specific equipment connected to the system. Further investigation into the sensitivity of critical equipment to voltage and current imbalances is recommended.

Conclusion and Recommendations

Conclusions

This energy efficiency assessment revealed significant imbalances in current and real power distribution, likely contributing to the observed voltage drops. The high CUF (44.2%) and large real power difference (59.8%) are the most pressing issues. The wide variation in power factor, and likely its low average value, also warrants attention.

The study concludes that the public facility has significant electrical imbalances and inefficiencies that need to be addressed. The key conclusions are:

1. *Significant Current Imbalance***:** The high Current Unbalance Factor (CUF) of 44.2% indicates a severe imbalance in current distribution across the three phases. This is likely the most pressing issue.
2. *Uneven Power Distribution***:** Both real and apparent power are distributed unevenly across the phases, with Phase C carrying a disproportionately higher load. This leads to inefficiencies and potential losses.
3. *Voltage Drops:* While the voltage unbalance is within acceptable limits, the study observed significant voltage drops, indicating potential issues with the distribution system.
4. *Variable and Likely Low Power Factor:* The power factor fluctuates widely, suggesting a likely low average value. This indicates a high reactive power demand, leading to increased current and losses.
5. *Interconnected Issues:* The study suggests that these issues are likely interconnected. The current imbalance probably contributes to the voltage drops and may also be impacting the power factor.

In short, the facility's electrical system is not operating efficiently or optimally. The imbalances are likely leading to increased energy consumption, higher operating costs, potential equipment stress, and reduced lifespan. Addressing these issues, particularly the current and power imbalances, offers significant opportunities for improvement.

Recommendations

The study recommends a multi-pronged approach to improve the facility's electrical efficiency. Primarily, the high current imbalance (44.2% CUF) demands immediate attention. This requires a thorough analysis of the loads connected to each phase, particularly Phase C, which carries a disproportionately large share of the current. A comprehensive inspection of electrical equipment, including motors and transformers, is also necessary to identify any potential faults contributing to the imbalance. Furthermore, the wiring system should be checked for proper sizing, secure connections, and any other issues that might exacerbate the problem. Ultimately, the goal is to redistribute loads across the three phases to achieve a more balanced current distribution.

In addition to addressing the current imbalance, the study recommends correcting the uneven distribution of both real and apparent power. This involves a detailed analysis of the power consumption of individual pieces of equipment connected to each phase. Based on this analysis, strategies should be implemented to balance the power drawn across all phases, similar to the load balancing efforts recommended for current.

The study also suggests evaluating and improving the power factor. The first step is to calculate the average power factor. If it falls below the recommended threshold (e.g., 0.9), power factor correction measures should be implemented. This typically involves installing power factor correction capacitors, with an initial focus on Phase C due to its higher apparent power demand.

While the voltage unbalance is within acceptable limits, the study identified significant voltage drops. Therefore, an investigation into the causes of these drops is recommended. This includes checking the conductor sizing to ensure it is adequate for the loads, assessing the length of cable runs as longer runs can contribute to voltage drop, and inspecting all electrical connections for tightness and proper installation to minimize resistance.

Finally, the study strongly recommends implementing a regular monitoring program. This program should track key electrical parameters such as voltage, current, power, and power factor. Regular monitoring will help identify trends, detect developing imbalances or inefficiencies early on, and provide an opportunity to take proactive measures to prevent future problems. It will also be essential in evaluating the effectiveness of the solutions implemented.

Before implementing any of the recommended solutions, it is strongly advised to conduct a formal cost-benefit analysis (CBA). This detailed analysis considers all relevant costs (initial investment, installation, maintenance, etc.) and benefits (energy savings, reduced demand charges, improved equipment lifespan, etc.) over the expected lifespan of the solution.

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