International Journal of Applied Power Engineering (IJAPE)
Vol. 13, No. 4, December 2024, pp. 952~962
ISSN: 2252-8792, DOI: 10.11591/ijape.v13.i4.pp952-962

Empowering industry through energy auditing: a case study of savings and sustainability

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Article Info

Article history:

Received Sep 23, 2023
Revised Jul 31, 2024
Accepted Aug 15, 2024

Keywords:

Energy audit
Energy efficiency
Energy sustainability
Energy-saving opportunities
Quality power analyzer

ABSTRACT

Conducting energy audits is pivotal in assessing industrial plant efficiency and formulating effective energy management plans. It identifies opportunities for efficient energy use, reducing costs and environmental impact. This study employs a techno-economic approach to analyze electricity cost reduction in an industrial facility. Through energy auditing, it explores economic benefits and improved energy quality, yielding favorable outcomes. Focused on a plastic derivative manufacturing plant, the study reveals critical audit findings. The main aim is to identify avenues for electric energy savings, cutting production costs, and enhancing product competitiveness. The audit involves a detailed analysis of consumption patterns, signal quality, and potential energy management strategies, culminating in a cost-cutting plan. The results of an economic assessment of the suggested energy-saving strategies, provide a comprehensive evaluation of their financial implications. It reveals significant cost reduction opportunities, estimating annual energy savings of $45,824.56, which represents a 23.68% decrease in expenses. These initiatives not only boost the plant's financial performance but also strengthen its competitive edge.

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1. INTRODUCTION

Energy audits play a pivotal role in enabling industrial firms or facilities to comprehensively assess their energy utilization, pinpointing areas of wastage and opportunities for enhancement [1], [2]. These recommendations are tailored to benefit both in-house auditors overseeing their facility and external consultants engaged in conducting the audit. Conducting an energy audit is instrumental in evaluating the energy efficiency of an industrial plant and formulating an effective energy management strategy. The audit process involves a meticulous verification, monitoring, and analysis of energy usage, culminating in the production of a technical report encompassing suggestions for heightened energy efficiency, cost-benefit analysis, and a targeted action plan to curtail energy consumption [3].

The objectives of an energy audit may vary from one facility to another, yet it is generally undertaken to gain a comprehensive understanding of energy utilization within the facility and to identify avenues for improvement and energy conservation. Additionally, energy audits serve as a means to appraise the efficacy of energy efficiency initiatives or programs. Numerous research endeavors are focused on curbing energy consumption through the implementation of energy audits. Thakare *et al.* [4] study offers a grounded perspective on the practical utility of energy audits as an effective means to reduce energy usage. This tool equips plant management with a quantitative grasp of the technical and economic viability of various energy conservation measures (ECMs). As per the findings of the energy audit, a small-scale manufacturing plant stands to save 6,226 kWh of electrical energy annually, representing a substantial 22.82% reduction in the plant's yearly energy consumption.

Farhoodnea *et al.* [5] employ a modified discrete firefly algorithm (IDFA) to enhance power quality in distribution systems. They tackle a multi-objective optimization problem to fine-tune the voltage profile, minimize voltage total harmonic distortion, and trim down overall investment costs. Boharb *et al.* [6] aim to unearth potential energy savings within the small and medium-sized paper industry. Through a comprehensive examination of energy consumption and electrical quality issues, they present the audit results along with their financial viability. The recommended energy efficiency measures promise to conserve approximately 347.85 MWh of electrical energy and 101.78 MWh of thermal energy, resulting in noteworthy savings of 11.48% and 2.22%, respectively. Numerous studies deal with enhancing the power qualities of the electric grid [7]–[9], by filtering the active [10] and reactive energy [11], moreover, metering energy consumption [12], [13] and planning the energy consumption in the electricity grid [14], in the other hand, some studies, suggest an efficient approach for optimal shunt capacitor allocation to minimize energy loss costs. It employs particle swarm optimization (PSO) [15] to enhance the power system reliability via high-speed control of electrical parameters by investigating the impact of static VAR compensators and distributed generation units on reliability this algorithm is devised to place these devices, considering cost-effectiveness while improving reliability optimally [16]–[18].

A groundbreaking energy auditing framework is employed in a practical water supply system and its corresponding subsystems to pinpoint the root causes of energy inefficiency [19]. This system has been integrated into the Portuguese national initiative for water-energy loss management. The scrutiny of the 17 subsystems uncovers that terrain constraints, water losses, and an absence of intermediate service pressure levels are the primary inefficiencies. Consuming nearly 20% of Germany's industrial energy, the chemical industry presents a significant opportunity for greenhouse gas reduction. This paper addresses the need for a comprehensive analysis by creating a marginal cost curve for energy efficiency measures in German chemical plants. We quantify uncertainties and identify key factors influencing potential savings, providing valuable insights for both energy planners and industry leaders [20]. Cai *et al.* [21] proposes a new multi-objective energy benchmark for the mechanical manufacturing industry. This method tackles the challenge of wasted energy due to complex processes by using energy consumption forecasts and integrated assessments. A case study demonstrates the method's effectiveness in achieving energy management and a potential 21.3% saving. Driven by rising energy costs, environmental concerns, and stricter regulations, manufacturers increasingly focus on optimizing energy use. This paper explores how the multiple linear regression approach can be used by automotive companies to identify and quantify factors impacting their plants' energy intensity. This knowledge empowers strategic decision-making and future energy demand forecasting [22].

Ibrik and Mahmoud [23] underscore the need for a thorough exploration of modern energy-efficient technologies. This study is spurred by the execution of a nationwide three-year project focused on bolstering energy efficiency across residential, industrial, and public utility sectors. It encompasses a diverse range of audits and power measurements. Based on these assessments, the collective potential for conservation in these sectors amounts to approximately 15% of the overall energy usage. The associated investment costs in this industry are relatively modest, with a payback period spanning from 6 to 36 months. A projected reduction of 10% in new energy procurement capacity is anticipated as a direct outcome.

The potential for energy-saving initiatives is particularly pronounced in the industrial sectors with the highest energy consumption, with cement factories being of paramount importance [24]. Indeed, the cement industry in Morocco grapples with substantial energy expenses, constituting over two-thirds of the total cement production costs. Specifically, electricity and fuel expenses make up 40% and 30% of the overall cement production costs, respectively. This underscores the need for concerted efforts to align the cement sector with the energy conservation targets outlined in Morocco's energy efficiency strategy. In a comprehensive study, Fellaou and Bounahmidi [25] conducted a thorough mass and energy balance analysis of an existing cement mill in Morocco. Before deploying them to calculate unmeasured variables, redundant measurements were rigorously validated using the Lagrange multipliers technique. The data pertaining to energy consumption and associated losses are meticulously presented across the entire production line [26], [27]. These findings have been leveraged to assess the process's energy performance.

This paper conducts an exhaustive electrical energy audit for an industrial process. This involves meticulously collecting data from electric bills, complemented by utilizing a high-quality energy analyzer and a thermography camera. The ensuing data is subjected to comprehensive analysis and discussion. Additionally, the paper explores avenues for reducing electricity consumption and undertakes an economic evaluation of potential tracks for reducing electric energy usage, employing an energy management approach. The paper unfolds in three main sections. Initially, it scrutinizes the company's electric bill under examination. Following this, a detailed analysis of the data collected from the quality power analyzer and thermography camera is presented. Finally, the third section focuses on the economic assessment of strategies to curtail electrical consumption.

2. METHODS: ELECTRICAL ENERGY AUDIT AND REDUCTION IN INDUSTRIAL PROCESSES

In the initial phase of our methodology, historical electric bills for the industrial process under investigation are diligently collected. Subsequently, a high-quality energy analyzer provides real-time data on critical electrical parameters, including voltage, current, power factor, and energy consumption. Following this, a thermography camera is deployed to capture thermal images of electrical components. This step is instrumental in identifying potential areas of inefficiency and overheating, thus forming a comprehensive foundation for our data-driven approach.

Our focus shifts to the analysis and evaluation stage with the data collected. Here, a meticulous examination of the gathered electric bills is conducted to gain profound insights into historical energy consumption patterns. Simultaneously, the data obtained from the quality energy analyzer is analyzed, enabling us to assess power quality, identify harmonic distortions, and pinpoint opportunities for improvement. Additionally, the thermal images captured are reviewed to detect hotspots and anomalies in electrical equipment, providing valuable indications of potential energy wastage.

Moving into the reduction strategies and economic evaluation phase, we transition seamlessly from our thorough analyses. This stage involves identifying energy reduction opportunities, where potential avenues for reducing electricity consumption are explored. These avenues include optimizing equipment operation, upgrading to more energy-efficient technologies, and implementing energy-saving practices. Following this, a comprehensive cost-benefit analysis ensues, evaluating factors such as upfront investment, expected energy savings, and payback period. Finally, the economic assessment informs the development of an energy management plan, outlining specific actions, responsible parties, and timelines for implementing the identified reduction strategies. This structured approach ensures a systematic and data-driven process towards achieving tangible energy efficiency improvements in industrial processes.

3. ENERGY ECONOMICS AND DATA ANALYSIS

3.1. Tariffs: Seasonal and time-of-day substation rates

In determining the cost of electrical energy, it remains crucial to factor in the total kilowatt-hours consumed and the specific period during which this consumption occurred. The electricity pricing structure primarily hinges on consumption within designated time slots in Table 1. Effectively managing these consumption hours holds the key to exerting greater control over the electricity bill and optimizing costs [15]. The consumed charge (CC) is calculated in (1) by summing up the consumption in each time slot based on the applicable tariff and chosen option. Where p_FH is the price per kWh of the full hour; p_PH is the price per kWh of the peak hour; HCP is the price per kWh of an off-peak hour; and Cons is active energy consumed during a time shift.

$$CC = p_{FH} * Cons\_p_{FH} + p_{PH} * Cons\_p_{PH} + P_{OPH} * Cons\_P_{OPH} \tag{1}$$

3.2. Standard tariff structure (MT)

The cost of consumed energy is calculated using a standardized tariff structure, as outlined in Table 2. This structure includes a fixed annual fee based on subscribed power in kVA. For example, a facility with 500 kVA of registered power would pay an annual fixed fee of $53.96 per kVA (including taxes). Additionally, a variable consumption fee is applied per kilowatt-hour consumed, with the price depending on the time of day. During full hours (FH), the rate is $0.10632/kWh. This price increases to $0.1490/kWh during peak hours (PH), and falls to a lower rate of $0.07787/kWh during off-peak hours (OPH). This time-based pricing structure incentivizes energy consumption during off-peak periods.

Table 1. Electricity pricing time slots

Classification	Period	Price for kWh HT	Price for kWh TTC
Full hours (FH)	07h--17h	0.886	1.063
Peak hours (FH)	17h--22h	1.242	1.490
Off-peak hours (OPH)	23h--07h	0.649	0.779

Table 2. Standardized tariff structure used to calculate the cost of consumed energy

Parameters	Value
Fixed fees for kVA/year	53.96 $
Taxes are included in 500 KVA of registered power per year in dollars	26,980.20 $
Consumption fee per kWh in dollars, including taxes	
Full hours (FH)	0.10632 $/kWh
Peak hours (FH)	0.1490 $/kWh
Off-peak hours (OPH)	0.07787 $/kWh

Electrical consumption data is collected monthly from meters installed at the high-voltage (HV) substation, as shown in Figure 1. This data provides a detailed picture of the facility's energy use. For instance, in 2021, the total electricity consumption for the industrial factory was 1,499,888 kWh. Based on the applicable tariff structure, this resulted in a total payment of $193,485.15 for electricity costs.

As depicted in Figure 2, industrial electricity consumption exhibits a seasonal pattern. A noticeable dip typically occurs in August, coinciding with factory vacation periods when production activities are reduced. Conversely, demand surges in October, January, March, and April. These fluctuations directly correlate with shifts in production levels driven by the industrial facility's order book. This highlights the close link between manufacturing activity and energy consumption within industrial settings.

The graph in Figure 3, presents power factor values for each month. Power factor measures how effectively electrical power is converted into sound work output. A perfect power factor is 0.95, while a lower value indicates less efficient power usage. In this case, the power factor varies throughout the year, with the lowest value occurring in August at 0.57 and the highest in July at 0.91. The annual average power factor is calculated to be 0.80. the power factors are below the desirable level of 0.80. This indicates a need for corrective measures to improve the power factor and prevent penalties. Specifically, aiming for a power factor of 0.95 would be beneficial in enhancing the quality of electrical energy usage. This improvement would lead to more efficient electrical power utilization and cost savings.

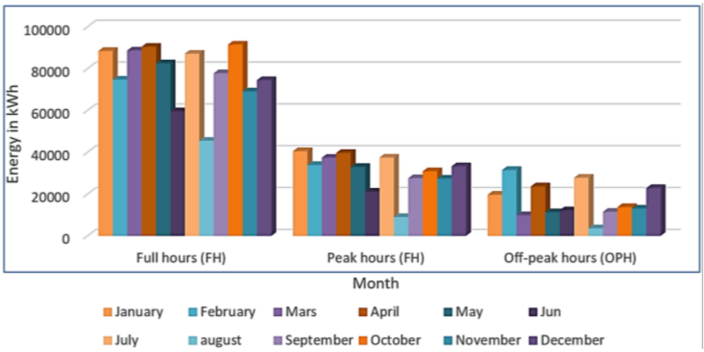

Figure 1. Evolution of energy cost ($) by time-of-day substation rates

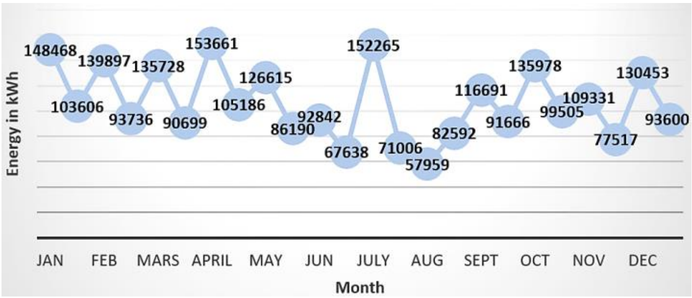

Figure 2. Energy consumption (kWh) in the industrial plastic factory

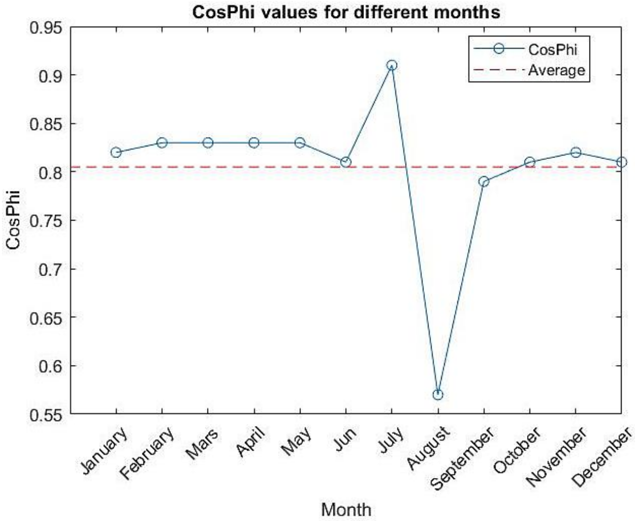

Figure 3. Cos Phi

4. ENERGY DIAGNOSTIC AND DATA COLLECTED USING A QUALITY POWER ANALYZER

A comprehensive set of measurements was conducted using highly accurate tools specifically tailored for the factory setting, namely the quality power analyzer and thermographic camera. The project's overarching objective is to eradicate energy loss and assess potential avenues for energy conservation. To achieve this, strategic locations for real-time diagnosis of electrical consumption were selected, encompassing a ten-day monitoring period, illustrated in Figure 4.

At the core of this endeavor, a power quality analyzer is intricately connected to the electrical supply using current transformer (CT) clamps and voltage sensors. This apparatus is strategically positioned at the output point of the transformer, directed toward the main electric substation. Observations reveal voltage fluctuations ranging from 384.58 to 412.57 V, attributed to the stochastic energy demands of various factory plant consumers in Figure 5. This voltage variability is particularly noticeable in the three phases, with noteworthy instances like Monday, December 27, 2021, marking a substantial surge in power demand from the factory plant. This surge, driven by electrical equipment usage, leads to voltage drops at the start of each production day. However, during nighttime hours, voltage values return to their typical levels.

Figure 4. Measurement using a quality power analyzer

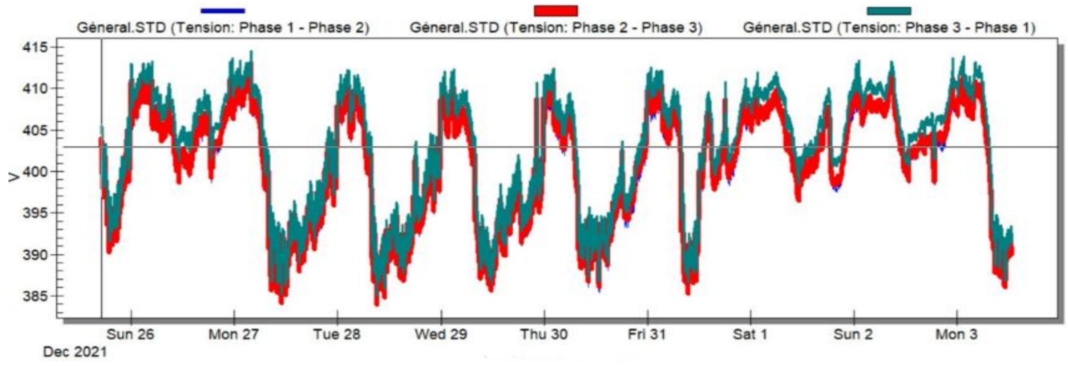

Figure 5. Time series measurements of interphase voltage

Meanwhile, in Figure 6, the curves present distinct current phases, with notable disparities among them. Phase 3 attains a maximum current of 373 A, whereas Phase 2 reaches 748 A. These disparities are further evident in the time series of active power measurements, which corroborate the aforementioned observations. Notably, production ceases each weekend from midnight Saturday until 06:00 on Monday.

Notably, on Mondays, precisely December 27 and January 3, there is a spike in apparent power demand immediately following the weekend hiatus when production resumes, as presented in Figure 7. The apparent power reflects the total amount of power supplied to the system, including both real power used to perform work and reactive power returned to the source. apparent power reaching up to 390 kVA, stemming from the heightened power needs of machinery such as compressors and other energy-consuming devices. It is crucial to mention that the factory's subscribed power capacity stands at approximately 500 kVA.

The analysis focused on measurements obtained from the quality power analyzer. The data unveiled a noteworthy pattern: during weekends with no production activity, the energy consumption remains constant at zero kWh from Sunday, December 26, 2021, until the commencement of Monday, December 27, 2021. This pattern repeats, showing a similar trend between Friday, January 1, and Monday, January 03, 2022, as presented in Figure 8.

The power factor must meet contract conditions with the electricity distributor [28], with a critical threshold set at 0.8. Dropping below this value incurs significant penalties. Capacitor banks are strategically placed within the electrical system to mitigate such penalties, as shown in Figure 9. According to the quality power analyzer data, the installation's average Cos Phi, recorded at approximately 0.779, falls short by 0.16. Maintaining this deficit could result in penalties, but improvements could bring Cos Phi closer to the recommended 0.95 threshold.

Harmonic distortion rates, assessed for voltage and current, provide crucial insights into potential grid pollution. Harmonic distortion levels below 5% typically have minimal impact, while levels above 10% can disrupt more robust equipment. In the current context, three-phase voltages show minimal distortion at 2.9%, while line currents for L3, L2, and L1 exhibit total harmonic distortion (THD) values of 40%, 20%, and 5%, respectively. Monitoring harmonic currents upstream allows for pinpointing the source of distortion, leading to overheating and disruptions in various equipment powered from the same source, as shown in Figure 10.

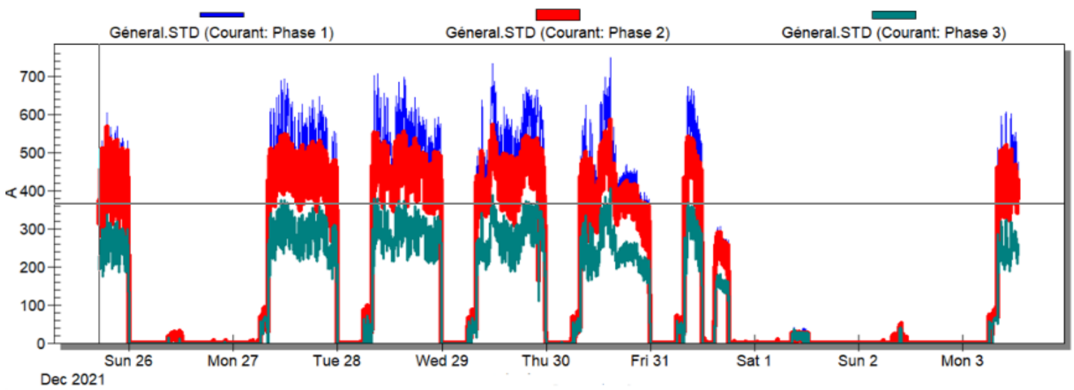

Figure 6. Time series measurements of interphase current

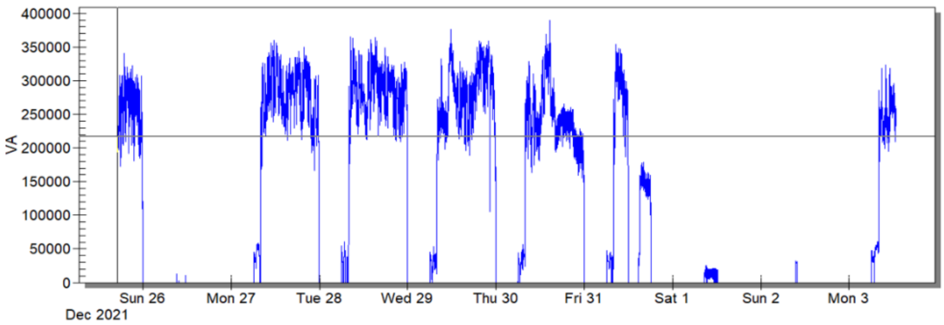

Figure 7. Time series measurements of the apparent power

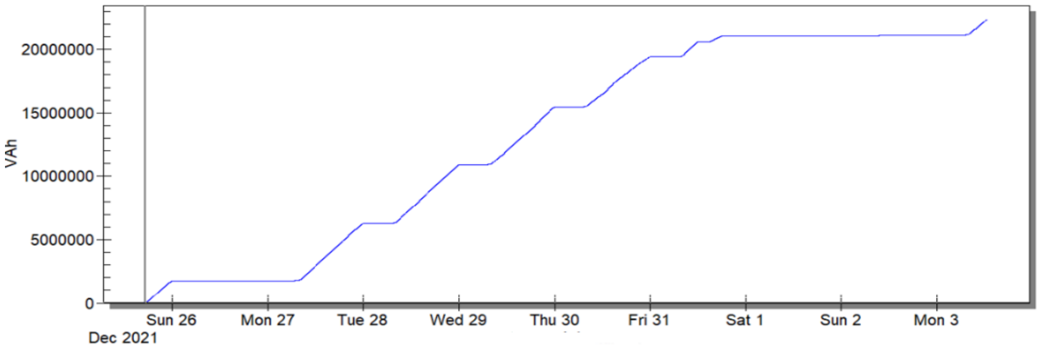

Figure 8. Measurements of the overall electrical energy consumption

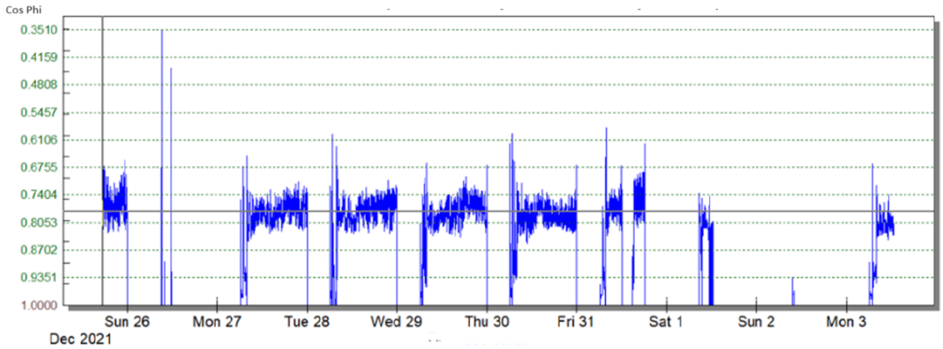

Figure 9. Monitoring Cos Phi fluctuations

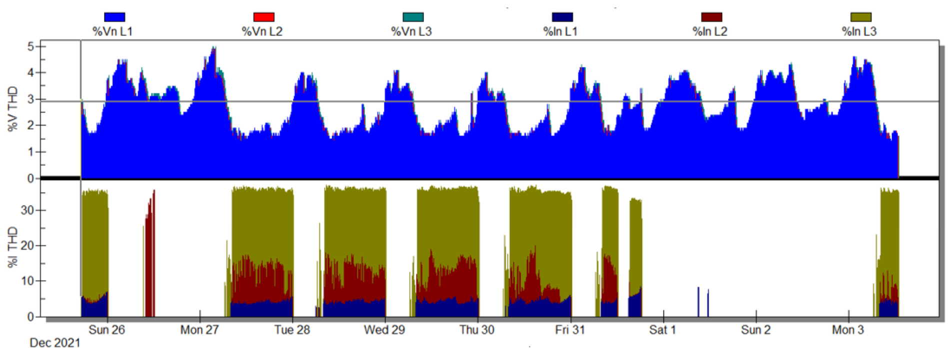

Figure 10. Measurements of the THD rate of harmonic distortion of the installation

5. RESULTS AND DISCUSSION

5.1. Improving the power factor

The energy audit at the factory plant assesses potential energy-saving and management opportunities. Compliance with the contract terms with the electricity distributor mandates a minimum power factor (Cos Phi) of 0.8, as shown in Table 3; failing to meet this threshold incurs substantial penalties. In this scenario, power factor surcharges amount to $4,587.08/year, while penalties for enhancing the power factor stand at $1,760.47/year, resulting in a total penalty of $6,347.55/year.

Table 3. Penalties due to power factor surcharge

Month	Cos Phi	Cos Phi penalty in $
January	0.82	0
February	0.83	0
March	0.831	0
April	0.825	0
May	0.826	0
June	0.808	0
July	0.906	0
August	0.574	4151.21
September	0.786	435.86
October	0.807	0
November	0.815	0
December	0.812	0
Total	0.80	4,587.08

Improving the power factor from 0.8 to 0.95 at the industry plant yields substantial financial benefits. This enhancement directly impacts the electric bill, potentially saving up to 5% annually, equivalent to $9,674.25. The total potential annual savings amount to $16,021.80. Adding reactive compensators, like capacitor banks, offers a dual advantage: optimizing component usage and increasing available power. Raising the power factor from 0.7 to 0.95 leads to a remarkable 36% boost in available power. The industry plant must bring back the Cos of Phi from 0.8 to 0.95, 131.88 kVAR of compensation batteries. Installing capacitor banks strategically in the electrical network is crucial for compensating reactive power, filtering harmonics, and enhancing power quality. The recommended capacity for the banks, including harmonic filtering, is 150 kVAR, requiring an investment of $15,000. This investment is projected to yield returns in roughly 11 months.

5.2. Implementing an energy management system for electric bill reduction

Energy management entails a comprehensive approach involving decision-making, technique implementation, and usage modifications aligned with a unified energy policy. It encompasses the procedures a company adopts to govern its energy consumption, all aimed at fostering constant improvement in energy efficiency. The primary objective of energy management is to continually enhance energy performance by achieving long-term reductions in energy consumption. Metering stations are pivotal in this endeavor, providing essential data for monitoring, controlling, and analyzing electrical networks. In the case of our factory plant, the total electric consumption in 2021 reached 1499,888.00 kWh, resulting in a corresponding payment of $193,485.15. Electricity pricing is intricately tied to consumption periods (as indicated in Table 1). Therefore, adept management of consumption schedules becomes imperative for effective control over the electricity bill.

Table 4 further illustrates the impact of hourly pricing on the final bill, differentiating between total hours (FH), off-peak hours (OPH), and peak hours (PH). Intriguingly, 32.6% of the total bill corresponds to a mere 24.7% of the energy consumed during peak hours (PH), primarily between 17h in winter, 18h in summer, and 23h. Notably, our industrial factory operates from 07 PM to 07 AM, and specific heavy electric machinery may operate partially during the off-peak period, indicating a potential avenue for optimization.

After 5 p.m. in winter (6 p.m. in summer), electricity consumption peaks at 370,527.00 kWh, constituting 24% of the plant's annual usage and a significant 32.56% of the total yearly bill of $55,216.67. Analysis of scenarios in Table 4, while maintaining the same consumption pattern, highlights Scenario 8 as the most optimal, potentially saving $31,563.23 annually. This scenario involves relocating 50% of consumption from peak to off-peak hours and 25% to full hours while retaining only 25% during peak times. Transitional Scenario 6 redistributes 25% of consumption from peak to off-peak, another 25% to full hours, and maintains 50% during peak hours, resulting in substantial savings estimated at $17,734.06. Achieving these objectives relies on shifting energy consumption from peak to alternative pricing periods, potentially yielding annual savings of $31,563.23.

Table 4. Scenarios of electricity consumption management according to a period of pricing

Scenarios		Peak hours (FH)	Full hours (FH)	Off-peak hours (OPH)	Economy in $
Scenario 1	Percentage %	100.00	0.00	0.00	0.00
	kWh Consumed	370,527.00	0.00	0.00	
	price in $	55,216.67	0.00	0.00	
Scenario 2	Percentage %	75.00	25.00	0.00	3,954.89
	kWh Consumed	277,895.25	92,631.75	0.00	
	price in $	41,412.51	9,849.27	0.00	
Scenario 3	Percentage %	50.00	50.00	0.00	7,909.78
	kWh Consumed	185,263.50	185,263.50	0.00	
	price in $	27,608.34	19,698.55	0.00	
Scenario 4	Percentage %	25.00	75.00	0.00	11,839.68
	kWh Consumed	92,631.75	277,895.25	0.00	
	price in $	13,804.17	29,547.82	0.00	
Scenario 5	Percentage %	75.00	0.00	25.00	13,779.16
	kWh Consumed	277,895.25	0.00	92,631.75	
	price in $	41,412.51	0.00	7,213.60	
Scenario 6	Percentage %	50.00	25.00	25.00	17,734.06
	kWh Consumed	185,263.50	92,631.75	92,631.75	
	price in $	27,608.34	9,849.27	7,213.60	
Scenario 7	Percentage %	25.00	50.00	25.00	21,663.95
	kWh Consumed	92,631.75	185,263.50	92,631.75	
	price in $	13,804.17	19,698.55	7,213.60	
Scenario 8	Percentage %	25.00	25.00	50.00	31,563.23
	kWh Consumed	92,631.75	92,631.75	185,263.50	
	price in $	13,804.17	9,849.27	14,427.21	

6. CONCLUSION

An effective comprehensive of the broader energy audit has successfully identified significant electrical energy-saving opportunities. This audit meticulously assessed the quality of power supplied throughout the electrical network, encompassing transformer stations, low-voltage switchboards, loads, and machines within the industrial facility. Through a rigorous techno-economic evaluation, we have demonstrated the potential to reduce the industrial plant's electricity expenses substantially. Our findings reveal various strategies that promise economic and energy quality improvements. Eliminating penalties due to the power factor alone can result in a substantial benefit of $4,587.08. Moreover, enhancing the power factor to 0.95 or higher directly translates into an impressive 5% reduction in the annual bill, amounting to $9,674.25. Furthermore, by intelligently shifting energy consumption away from peak hours to alternative pricing periods, we've unveiled the potential for annual bill savings estimated at $31,563.23.

In totality, the electrical energy-saving opportunities identified through examining power quality supplied by the energy distributor amount to a substantial $45,824.56 annually. This represents an average energy-saving potential of 23.68%. These findings underscore the significance of energy auditing and highlight the significant economic and sustainability benefits of implementing recommended measures. Optimizing the power factor and incorporating reactive compensators in the factory plant's electrical system results in significant cost savings and enhances efficiency and capacity with a rapid return on investment.

ACKNOWLEDGEMENTS

The author extends gratitude to the physics department of the Faculty of Sciences and Technics (FST-Settat) at Hassan First University in Settat (UHP), Morocco, as well as to the industrial plant and its dedicated team for their cooperation and contributions to the successful completion of this endeavor.

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