ISSN: 0975-833X

Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 18, Issue, 10, pp. 38689-38697, October, 2026
DOI: https://doi.org/10.24941/ijcr.50951.10.2026

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

RESEARCH ARTICLE

ENERGY AUDIT OF A BEVERAGE PLANT IN A SAHELIAN CONTEXT: QUANTIFIED SAVING POTENTIALS, GENERATOR-SET EFFICIENCY DEFICIT AND METROLOGICAL VALIDATION OF THE MEASUREMENT CAMPAIGN

Souleymane Ramdé[1,2], Hassime Guengané[1], Abdel Kader Hounsoubo Lingani[1] and Inoussa Lankoandé[3]

[1]Joint Laboratory in Engineering Sciences, Ecole Polytechnique de Ouagadougou, Burkina Faso; [2]University of Lédéa Bernard Ouédraogo, Ouahigouya, Burkina Faso; [3]Burkina Elite, Ouagadougou, Burkina Faso

ARTICLE INFO

Article History:
Received 24th July, 2026
Received in revised form
20th August, 2026
Accepted 15th September, 2026
Published online 30th October, 2026

Key words:

Energy Audit; Industrial Energy Efficiency; Reactive-Energy Compensation; Measurement Validity; Generator Set; Specific fuel Consumption; Sahel.

***Corresponding author:**
Souleymane Ramdé

ABSTRACT

Agro- industries in the Sahel face high energy costs. They depend on a constrained public grid, they suffer frequent supply interruptions, and they rely on standby generator sets. This paper reports the energy audit of a beverage plant in West Africa. The audit uses four data sources: the electricity and fuel invoices for 2021–2024, manufacturer data, operating reports, and a power-quality measurement campaign. A key feature of the method is that the four sources are not treated as equally reliable. Each source is first checked, then each saving potential is classified according to the quality of the data that supports it. The measurement campaign was found to be invalid for power calculations, because two of the three current transformers are connected with reversed polarity and because the analyser was installed on a sub-feeder rather than at the plant intake. All conclusions were therefore re-anchored on the billing records, which are independent of the instruments. The audit gives an annual electricity consumption of about 685 470 kWh for a bill of 80.2 million FCFA. Three potentials are retained, for a total of 6.2 to 8.4 million FCFA per year, that is 7.7 % to 10.5 % of the bill. The largest one concerns reactive-energy compensation. The billing coefficient has remained at exactly 1.000 since November 2023, so the plant receives no bonus, whereas the same installation held the best attainable value of 0.920 for eight consecutive months in 2022. The target is therefore a capability that was reached and then lost, which is worth 4.2 to 6.4 million FCFA per year depending on the tariff base. A fourth item, the subscribed-power penalty of 4.96 million FCFA per year, is identified but excluded from the total, because the net saving depends on the fixed charge per subscribed kW, which was not available. For the generator sets, a two-point Willans fuel law shows that low-load operation explains at most one third of the gap between the rated 3.91 kWh/L and the observed 2.20 kWh/L. At least 1.15 kWh/L of the gap comes from another cause, which a resizing would not correct. The audit therefore provides both a costed action plan and an explicit statement of how far each result is supported by the data.

Copyright©2026, Souleymane Ramdé et al. *This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.*

Citation: ***Souleymane Ramdé, Hassime Guengané, Abdel Kader Hounsoubo Lingani and Inoussa Lankoandé,*** **2026.** "Energy audit of a beverage plant in a Sahelian context: quantified saving potentials, generator-set efficiency deficit and metrological validation of the measurement campaign.*". International Journal of Current Research*, 18, (10), 38689-38697.

INTRODUCTION

Energy is one of the main cost items of agro-industries. It is used at every stage of production, for pumping, refrigeration, heating, packaging and handling. In Sahelian countries this cost is increased by a high electricity price, by a variable supply quality, and by the frequent use of generator sets to keep production running. Energy efficiency is therefore a competitiveness issue and not only an environmental one (1,2). Energy audits are the usual tool for finding losses, assessing equipment performance, and proposing corrective actions that are technically and economically realistic (3,4). In the food and beverage sector, savings have been reported from power-factor improvement, better management of electrical demand, improvement of industrial refrigeration, and the use of renewable sources (5,6). Most of these case studies come from contexts where the electrical infrastructure is stable and the measuring instruments are reliable. Data on the energy performance of agro-industrial plants in West Africa remain limited (7). Studies from the sub-region deal mainly with the barriers to energy efficiency rather than with plant-level audits (17,18). The configuration studied here is not represented in the published literature: a plant whose supply continuity depends on heavily oversized standby generation, whose demand profile is that of an under-used installation, and whose own measurement records turned out to be unreliable. Three gaps follow from this. First, published audits of food plants usually give an overall saving percentage without separating

the mechanisms behind it, so the reader cannot judge how transferable the result is. Second, generator-set inefficiency at low load is usually described in qualitative terms, whereas the manufacturer fuel law allows the part of the deficit that comes from low load to be separated from the part that does not. This separation determines whether the correct action is a resizing or an engine overhaul. Third, and most important, the validity of the measurement campaign on which an audit rests is rarely assessed in print, although connection faults on instrument transformers are common in industrial installations and make the derived power values meaningless (8). The objective of this study is to identify, quantify and rank the main energy-saving potentials of a beverage plant (juices, nectars and carbonated drinks) located in Sahelian West Africa. The contributions are the following:

- A classification of the audit data by level of reliability, and of each saving potential by the level of evidence that supports it, so that demonstrated results are not mixed with conditional ones;
- The demonstration, from four years of billing coefficients, that the reactive-compensation target used here is a performance that was previously achieved and then lost, rather than a theoretical objective;
- A Willans-line decomposition of the generator-set efficiency deficit, with a sensitivity analysis that gives a lower bound on the part that low load cannot explain;
- A metrological check of the measurement campaign that identifies a current-transformer polarity fault and states which conclusions depend on the instruments and which do not;
- A sensitivity analysis of the two assumptions that carry most of the economic result.

Section 2 describes the installation, the data and the method, including the reliability classification. Section 3 gives the baseline. Sections 4 to 7 examine the four families of potential. Section 8 reports the metrological check. Section 9 consolidates the potentials and gives the sensitivity analysis. Section 10 discusses the results and the limits, and Section 11 concludes.

MATERIALS AND METHODS

Description of the installation: The plant is supplied by the public distributor at 33 kV medium voltage, with high-voltage metering. The supply is stepped down to low voltage (400/230 V) by four transformers: one of 1 250 kVA for the control circuits, two of 1 000 kVA for the production lines, and one of 400 kVA for offices and auxiliary uses. At the time of the audit, all loads were carried by a single 1 000 kVA transformer. The 1 250 kVA and 400 kVA units were unused and the second 1 000 kVA unit was out of service. Supply continuity during load shedding is provided by two generator sets of 1 100 kVA each. This configuration explains several results reported below. Because only one transformer is energised, only one of the associated compensation batteries is active, which affects the reactive-energy behaviouranalysed in Section 4. Because the standby capacity of 2 200 kVA was sized for the complete four-transformer installation, it is now much larger than the demand actually carried, which affects the generator-set analysis of Section 5.

Data sources and their reliability: The audit used four data sources. They are not of equal quality, and the analysis treats them differently. Table 1 states, for each source, the period covered, the reliability assessment made during the audit, and the use that was made of it. This classification was established before the results were consolidated, and it is applied consistently in Sections 3 to 9.

Table 1. Data sources of the audit, reliability assessment and use made of each source

Source	Period	Reliability assessment	Use in this study
Electricity and fuel invoices from the distributor	2021–2024, monthly	Validated. Internally consistent over four years; independent of the plant instruments	Baseline consumption, billing coefficient, penalties, maximum demand
Manufacturer technical data (generator sets)	Nameplate and datasheet	Partly validated. Single source, not verified by test	Fuel law of Section 5, with sensitivity analysis
Operating reports of the plant	Reference year	Partly validated. Manually recorded, not cross-checked	Fuel consumed and energy generated, equipment inventory
Network-analyser campaign	6–9 August, with a 24 h gap	Invalidated for power quantities. Reversed polarity on two current channels; measurement taken on a sub-feeder	Qualitative diagnosis only (voltage range, phase imbalance). No power or demand value is derived from it

The consequence of the last line is important and is developed in Section 8. No result reported in this paper is derived from the summed three-phase power measured during the campaign. The maximum demand used in Section 5 comes from the demand recorded by the distributor for billing purposes, which is an independent source.

Economic conventions and assumptions: All monetary values are given in FCFA. The average tariff of 117 FCFA per kWh was obtained by dividing the total cost of all invoices since the start of production by the total number of kWh consumed up to the beginning of the study. This average tariff includes fixed charges, energy charges and penalties. It is therefore suitable for valuing quantities of energy, but not for valuing a change in the tariff structure itself. The subscribed-power item of Section 6 is accordingly treated separately, from the invoiced penalties.

Four assumptions are used:

H1. The annual bill of 80.2 million FCFA and the average tariff are representative of the period studied.

H2. The billing coefficient applies to the whole invoiced amount, so that a reduction of the coefficient reduces the bill in the same proportion.

H3. The two manufacturer fuel-consumption points of the generator sets correspond to 25 % and 100 % of the standby rating.

H4. The operating regime of the reference year is representative of future operation.

H2 and H3 carry most of the economic result. Both are uncertain, and both are tested by a sensitivity analysis in

Section 9.2. The values given in Sections 4 and 5 are those obtained under H2 and H3; the ranges obtained when these assumptions are relaxed are given in Section 9.

Baseline energy and cost profile: A quantitative baseline is needed before the potentials can be ranked, and it can be reconstructed from the invoices alone. At an average tariff of 117 FCFA/kWh, an annual bill of 80.2 million FCFA corresponds to an annual electricity consumption of about 685 470 kWh. Referred to the 350 kW subscribed power, this represents about 1 959 equivalent full-load hours per year, or roughly 22 % of the 8 760 hours of the year. This figure should be interpreted with care. A low number of equivalent full-load hours is compatible with a plant that is under-used, but it is also compatible with a plant that operates seasonally, or with one whose load is concentrated in a small number of shifts. The production data needed to distinguish between these explanations were not available. What can be stated without ambiguity is the consequence for the economics: a charge that does not depend on the energy consumed, such as the reactive-energy coefficient or the subscribed-power charge, weighs more heavily on a plant with few equivalent operating hours than on one running continuously. This is why the potentials identified in this study are concentrated on the structure of the invoice.

The baseline remains incomplete in one respect. No specific energy consumption indicator, relating energy consumed to physical production, was available. Such an indicator is the standard basis for comparing a site with sector references, and for checking, after the works, that a saving is real and not the result of a fall in output (9). Its absence is itself a finding of the audit. It also means that this study cannot state whether the energy intensity of the plant is high or normal, and no such claim is made.

Reactive-energy compensation: The tariff applies an energy-management coefficient (1 + m) that depends on the reactive energy consumed. Below unity it gives a bonus of up to 8 %; at unity it is neutral; above unity it gives a penalty. Each transformer has static compensation batteries (75, 100 and 22 kVAR) and each low-voltage main switchboard has dynamic batteries (300, 450 and 100 kVAR). One of them is shown in Fig. 1. Since only one transformer is in service, only one battery is active.



Fig. 1. Capacitor bank installed at the low-voltage main switchboard

Fig. 2 shows the monthly values of the coefficient over the four years. In 2021, before any compensation was in service, the coefficient was irregular and reached 1.100 in April, which generated penalties. After a first compensation battery was commissioned, the coefficient fell through 2022 and settled at exactly 0.920, the best attainable value, from May 2022 onwards. It stayed there for eight consecutive months. It then drifted upwards through 2023, between 0.920 and 0.942, rose to 1.000 in November 2023, and has remained at exactly 1.000 during all the months of 2024 covered by the record.

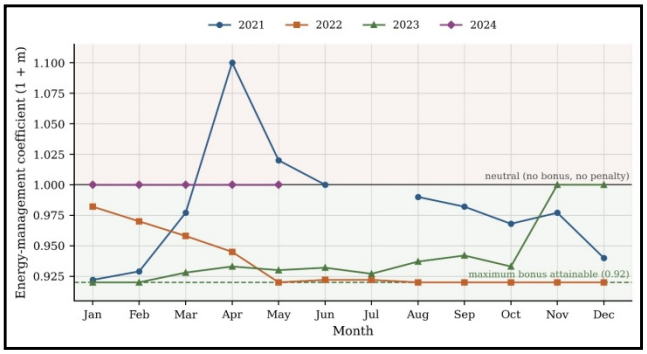

Fig. 2. Monthly values of the energy-management coefficient (1 + m) for 2021–2024. The dashed line marks the best attainable bonus (0.920) and the solid line the neutral value (1.000)

The present situation is therefore a loss of performance and not a stable operating point. A coefficient that stays at exactly 1.000 for fourteen months, with no variation from one month to the next, strongly suggests that the compensation is no longer regulating. Several explanations are consistent with this observation: a battery that has been disconnected, a regulator that is blocked, a loss of capacitor steps, or a change in the load or in the tariff rules. The available data do not allow these explanations to be separated, and an electrical diagnosis on site is required. What the record does establish is that the value of 0.920 was reached and held with the equipment already installed. This changes the economic reading. If the four-year average coefficient of 0.965 is taken as the reference, the saving is 4.5 % of the bill. But the relevant reference is the situation that actually prevails, namely 1.000, and the relevant target is the value already demonstrated by this installation, namely 0.920. The difference is 8 %. Under H2, that is 6.42 million FCFA per year. If the coefficient applies only to the active-energy component of the invoice, which is the more common arrangement in industrial tariffs, the saving falls in proportion; Section 9.2 gives the range. Because 0.920 was held for eight months with the existing equipment, the required action may be a repair and a re-setting of the existing compensation rather than a complete re-equipment. In that case the investment would be lower than the 6.25 million FCFA estimated, and the payback shorter. The recommended actions are: an electrical diagnosis of the active battery and of its regulator, to find out why the coefficient stopped varying in November 2023; a resizing of the compensation to the load actually carried by the single energised transformer, since the existing capacities were distributed over four transformers; and continuous monitoring of the coefficient with an alarm threshold, so that a future loss of compensation is detected within one billing period instead of fourteen.

Sizing and efficiency of the generator sets: The two 1 100 kVA sets, shown in Fig. 3, give an installed standby capacity of 2 200 kVA. The maximum demand recorded by the distributor

is about 440 kVA including the extension margin, that is 40 % of the rating of one set and 20 % of the installed capacity. The sets therefore run well below their design range. Prolonged operation at low load is known to cause fouling, incomplete combustion and premature wear, and to reduce efficiency (10).



Fig. 3. One of the two 1 100 kVA standby generator sets.

The operating reports give a specific output of 2.20 kWh per litre of diesel in the worst case. Rather than compare this value with a general expectation, it is more useful to compare it with the fuel law of the sets themselves. The manufacturer data give a consumption between 65 and 225 L/h according to load. Taking the rated electrical output of one set as 880 kW at a power factor of 0.8, and associating the two consumption points with 25 % and 100 % of load (assumption H3), the fuel consumption follows the usual affine Willans relation

$$\text{Fuel (L/h)} = a + b \cdot P, \quad \text{with } a = 11.7 \text{ L/h and } b = 0.2424 \text{ L/kWh} \qquad (1)$$

in which the constant term a represents the consumption that does not depend on load. This is an approximation, and the two coefficients are calibrated on only two manufacturer points, so the curve should be read as an order of magnitude and not as a measured characteristic. The corresponding specific output P/(a + bP) is plotted in Fig. 4. At rated load it is 3.91 kWh/L, and at the 40 % load actually observed it is 3.63 kWh/L.

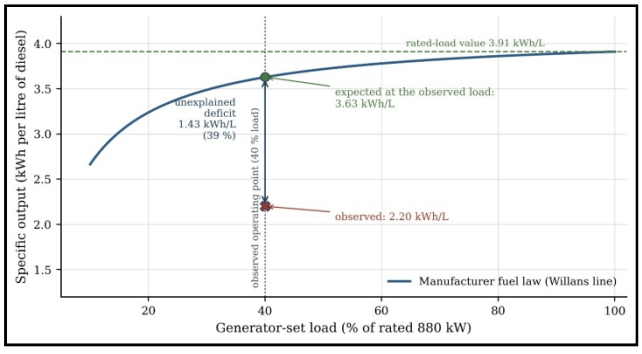

Fig. 4. Specific output of the generator sets against load, derived from the two manufacturer fuel points, and position of the observed operating point. The curve is a two-point approximation

Under H3, low-load operation explains 0.28 kWh/L of the total gap between the rated 3.91 kWh/L and the observed 2.20 kWh/L, that is 16 % of the gap, and the remaining 1.43 kWh/L is not explained by the operating point. This split depends on H3, so it was tested by varying the load associated with the 65 L/h point. Two constraints apply. First, the constant term a cannot be negative, which requires that point to lie at or below 28.9 % of rated load. Second, at 28.9 % the constant term vanishes and the fuel law becomes proportional, so low load explains none of the gap. Table 2 gives the result.

Table 2. Sensitivity of the generator-set analysis to assumption H3.

Load assumed for the 65 L/h point	a (L/h)	Expected at 40 % load (kWh/L)	Explained by low load (kWh/L)	Share of the gap
20 % of rating	25.0	3.35	0.56	33 %
25 % of rating (H3)	11.7	3.63	0.28	16 %
28.9 % of rating (limit, a = 0)	0.0	3.91	0.00	0 %

The conclusion that does not depend on H3 is therefore the following: whatever the load associated with the lower manufacturer point, low-load operation explains at most one third of the gap, and at least 1.15 kWh/L, that is at least two thirds of the gap, comes from another cause. This bound is the result that should be retained. It has a direct practical consequence: resizing the standby capacity would recover at most one third of the deficit. The dominant part points to one of three causes that a resizing would not address: a deterioration of engine condition consistent with the low-load operating history, an error in the fuel or energy metering from which the ratio is computed, or fuel losses between delivery and use. A controlled load-bank test with metered fuel is needed to separate them, and it should be carried out before any investment decision.

Subscribed-power overruns: The subscribed power was initially 130 kW and was raised to 350 kW in September 2023. Overruns, invoiced as penalties, remained frequent. Table 3 and Fig. 5 give the cumulated overrun powers and the corresponding penalties.

Table 3. Subscribed-power overruns and associated penalties, 2021–2024

Year	Cumulated overrun (kW)	Penalty (FCFA)	Unit rate (FCFA/kW)
2021	1 016	3 596 640	3 540
2022	2 089	7 395 060	3 540
2023	1 898	6 718 920	3 540
2024 (5 months)	626	2 065 800	3 300
Cumulative	5 629	19 776 420	–
2024 annualised	1 502	4 956 000	3 300

Two observations follow. First, the unit penalty rate is stable at 3 540 FCFA/kW over 2021–2023 but falls to 3 300 FCFA/kW in 2024. This difference comes either from a tariff revision or from a recording error, and it should be confirmed with the distributor. Second, raising the subscription from 130 to 350 kW did not remove the overruns. Extrapolating the five recorded months of 2024 to a full year gives 1 502 kW of cumulated overrun and about 4.96 million FCFA of annual penalty, a level close to that of 2021.

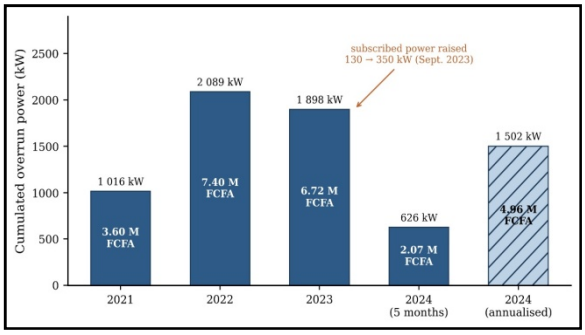

Fig. 5. Cumulated subscribed-power overruns and associated penalties, 2021–2024. The hatched bar extrapolates the five recorded months of 2024 to a full year

This penalty is a real and recurring cost. It is not, however, a demonstrated saving, and it is not counted in the consolidated total of Section 9. Removing the penalty requires the subscribed power to be raised, which increases the fixed charge. The net saving is

$$S = Ppenalty - cf \cdot \Delta P \qquad (2)$$

where Ppenalty is the penalty avoided, cf the annual fixed charge per subscribed kW, and ΔP the additional power subscribed. The measure is worthwhile only if cf is below the break-even value Ppenalty/ΔP. Table 4 gives that break-even value for several increments. Neither cf nor the peak demand that determines ΔP was available, so the net saving cannot be computed here. This is stated as a limit of the study rather than presented as a result.

Table 4. Break-even annual fixed charge below which raising the subscribed power is economically justified, for an avoided penalty of 4.96 million FCFA per year

Additional power subscribed ΔP	Break-even fixed charge cf	Interpretation
25 kW	198 400 FCFA/kW·year	Measure almost certainly worthwhile
50 kW	99 200 FCFA/kW·year	Measure very probably worthwhile
100 kW	49 600 FCFA/kW·year	To be checked against the tariff
200 kW	24 800 FCFA/kW·year	May not be worthwhile

Independently of the subscription level, continuous monitoring of the demand and peak-shaving devices, using battery storage or photovoltaic generation, would reduce the peak itself and therefore the power that has to be subscribed (11,12).

Other loads and potentials

No-load operation of the conveyors: At the start-up of the carton line, about one hour passes before the first units come out of the cooling tunnel. This delay is imposed by the pasteurisation and cooling steps needed for product quality. During this hour the conveyors run without carrying product. The carton line is driven by seven motors of 0.55 kW and the carbonated-drink line by three motors of 0.75 kW, that is 6.10 kW of installed motor capacity running with no product for at least one hour per start-up.

The energy involved must be estimated from the power actually absorbed and not from the rated power. An induction motor driving an unloaded conveyor absorbs only the power needed for belt friction and for its own losses, typically 30 % to 50 % of its rating. On that basis, and for about 300 start-up hours per year, the avoidable consumption is between 550 and 920 kWh per year, that is between 0.06 and 0.11 million FCFA. A calculation based on rated power would give 3 000 kWh per year, but it would assume that the motors absorb their full rating with no product on the belt, which is not physically correct. The measure is still worth applying, because synchronising the conveyor start with the tunnel output costs nothing, but its weight in the action plan is an order of magnitude smaller than a rated-power estimate suggests.

Cold rooms: The cold rooms are installed in the open air and therefore receive an increased thermal load. Published work on the energy efficiency of cold stores indicates that a rise in ambient temperature increases the electrical consumption of the refrigeration system by a few per cent per additional degree, the exact value depending on the design and on the operating conditions (13–15). Shading or relocating the units is therefore a plausible potential. It is deliberately not costed here, because quantifying it would require the refrigeration consumption to be sub-metered and the ambient and set-point temperatures to be recorded, and neither was available. It is kept as a qualitative recommendation and is excluded from the consolidated total.

Solar substitution for lighting and pumping: Replacing the electrical floodlights by autonomous solar units removes their consumption from the grid-supplied load. Table 5 gives the corresponding energy and cost at the average tariff.

Table 5. Energy and cost of the floodlights, and gross saving from solar substitution

Period	Energy (kWh)	Substitution rate	Gross saving (FCFA)
Monthly	1 368	100 %	160 056
Annual	16 416	100 %	1 920 672
Over three years	49 248	100 %	5 762 016

The annual floodlight consumption is about 2.4 % of the total electricity consumption of Section 3. The substitution rate of 100 % assumes that the solar units are fully autonomous, with storage sized for the whole night-time duty. The capital cost was not available, so no payback can be given and this item is classified as conditional in Section 9. The same applies to the water-supply system, for which replacing the submersible pumps by hybrid solar-and-grid units is recommended, subject to the same costing requirement.

Power-quality measurements and metrological check: The measurements recorded from 6 to 9 August are shown in Fig. 6. Voltage (a) and frequency stayed within the admissible ranges, except for a dip to about 219 V at the very end of the recording, which coincides with a current peak of about 175 A (b) and is consistent with an on-load voltage drop (16). The currents are clearly unbalanced: phase 3 is systematically higher than phases 1 and 2 over the whole observation, by a factor of about 1.7 during steady operation. A redistribution of the single-phase loads across the three phases is therefore recommended.

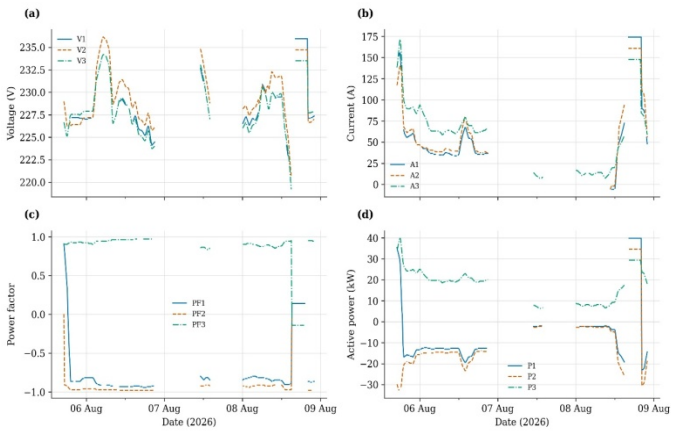

Fig. 6. Hourly trends of the main electrical parameters over 6–9 August: (a) phase voltages, (b) phase currents, (c) power factors, (d) active powers. The persistent negative sign of PF1, PF2, P1 and P2 indicates a current-transformer polarity fault on two of the three channels

Table 6. Consolidated saving potentials, with ranges and level of evidence

Measure	Annual saving (M FCFA)	Share of the bill	Level of evidence	Payback
Restoration and resizing of reactive compensation	4.2 – 6.4	5.2 – 8.0 %	Demonstrated	1.0 – 1.5 year
Solar substitution of the floodlights	1.82 – 2.02	2.3 – 2.5 %	Conditional (capital cost missing)	not determined
Synchronisation of the conveyor start-up	0.06 – 0.11	0.1 %	Demonstrated	immediate
Total retained	6.2 – 8.4	7.7 – 10.5 %	–	–
Subscribed-power penalty (gross)	4.96	6.2 %	Not quantified as a net saving	see Table 4
Generator-set efficiency deficit	not quantified	–	Not quantified (fuel data missing)	–
Shading of the cold rooms	not quantified	–	Not quantified	–
Hybrid solar pumping	not quantified	–	Not quantified (capital cost missing)	–

Table 7. Sensitivity of the main results to the assumptions and to the input data

Parameter varied	Range tested	Effect on the result	Robustness
Base to which the coefficient (1 + m) applies (H2)	Whole invoice, or active-energy component only (65 – 80 % of the invoice)	Reactive saving 4.17 to 6.42 M FCFA/year	The measure remains the largest potential in every case
Load associated with the 65 L/h fuel point (H3)	20 % to 28.9 % of rating	Share of the fuel gap explained by low load: 0 to 33 %	At least two thirds of the gap is unexplained in every case
Average tariff	117 FCFA/kWh ± 10 %	Floodlight saving 1.73 to 2.11 M FCFA/year; baseline consumption 623 000 to 762 000 kWh	Ranking of the measures unchanged
Cost of the compensation works	3.0 to 6.25 M FCFA	Payback 0.5 to 1.5 year	Measure remains worthwhile over the whole range

The power factor (c) and the active power (d) of phases 1 and 2 keep an almost constant negative sign. PF1 goes from +1 to −0.9 within the first measurements and PF2 never becomes positive again, while the shapes of |P1| and |P2| follow the same variations as P3. This combination is much more consistent with a polarity fault on the current transformers of these two channels than with a real electrical phenomenon such as reverse power flow, which would not preserve the correlation with the third phase (8). This finding has a consequence beyond the measurement itself. If two of the three current channels are reversed, the three-phase active power summed by the analyser is not the power delivered to the installation. With P1 ≈ −13 kW, P2 ≈ −14 kW and P3 ≈ +20 kW, the instrument returns about −7 kW where the corrected sum would be about 47 kW. Every quantity derived from the summed power over this campaign is therefore unusable as recorded, and correcting the polarity requires the raw per-phase data rather than the aggregated values. A second, independent check shows that the campaign does not characterise the whole installation in any case. A peak current of about 175 A on a 400 V three-phase system corresponds to an apparent power of about 121 kVA. This is not compatible with the 440 kVA maximum demand recorded for billing, nor with the 350 kW subscribed power that is regularly exceeded. The analyser was therefore connected to a sub-feeder and not to the plant intake. This is why the demand figure used in Section 5 is taken from the distributor records and not from this campaign, as stated in Table 1. The conclusion on generator-set oversizing is unaffected, because it rests on the billing demand and on the installed capacity of 2 200 kVA. The power-quality characterisation of the plant as a whole is affected, and has to be repeated. A recording gap of about 24 hours between 7 and 8 August further limits any indicator computed over the whole period. The campaign should be repeated at the plant intake, after the current-transformer polarity has been checked, with continuous recording over at least one full production week.

Consolidated potentials and sensitivity analysis

Classification and consolidated total: Table 6 and Fig. 7 consolidate the potentials. Each one is given with a range rather than a single value, and with the level of evidence that supports it. Three levels are used. A demonstrated potential rests on the validated billing data and on a target that the installation has already achieved. A conditional potential is quantified in energy terms but lacks either a capital cost or a tariff element needed to establish the net saving. A potential that is not quantified is identified but carries no figure. Only demonstrated and conditional potentials enter the total; the subscribed-power item of Section 6 is reported separately. The retained total is therefore 6.2 to 8.4 million FCFA per year, that is 7.7 % to 10.5 % of the annual bill. If the subscribed-power measure proves fully worthwhile once the fixed charge is known, the total would rise to between 11.2 and 13.4 million FCFA, that is up to 16.7 % of the bill. That upper figure is an upper bound and not a result of this study. The structure of the ranking is itself a finding. The leading measure is a restoration of a capability the installation already had, and the second item in size, the subscribed-power penalty, is a tariff question. Measures requiring investment in new technology, mainly the solar substitutions, come next. In the regional literature and in current practice, solar integration is usually presented as the first lever for industrial energy performance in the Sahel. The evidence collected here suggests that a billing and compensation audit should come first.

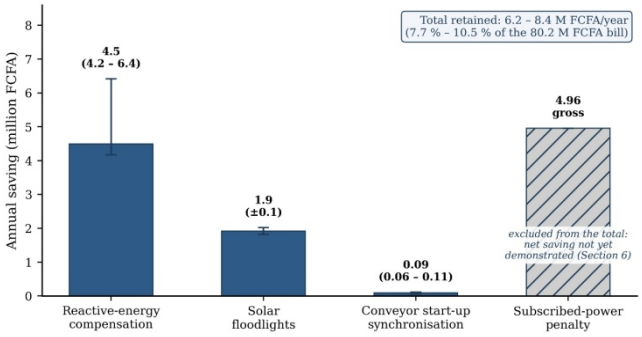

Fig. 7. Quantified annual saving potentials with their ranges. The hatched bar is the subscribed-power penalty, which is identified but excluded from the total because its net saving is not established

Sensitivity analysis: Four quantities were varied to test how far the consolidated result depends on the assumptions. The results are given in Table 7. The conclusion of this analysis is that the ranking of the measures is robust, whereas the absolute values are not. The reactive-energy potential remains the largest under every combination tested, and the fuel deficit remains mostly unexplained by load under every value of H3 that is physically admissible. The absolute figures should therefore be read as orders of magnitude with a spread of roughly plus or minus 25 %, and not as precise amounts. For the same reason, the payback periods are given to one decimal place at most, and the value of about one year quoted for the compensation should be understood as between six months and eighteen months.

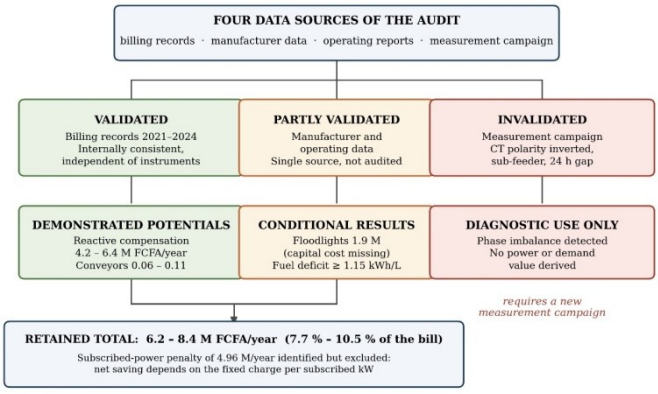

Fig. 8. Synthesis of the audit: from the four data sources to the retained potentials, through the reliability assessment of each source. Only results supported by validated or partly validated data enter the consolidated total

DISCUSSION

Comparison with the literature: The retained potential of 7.7 % to 10.5 % of the electricity bill is at the lower end of the range reported for factory-scale audits of food plants, where identified savings of 10 % to 25 % are common and are also dominated by management measures rather than by equipment replacement (7). The lower value obtained here is a direct consequence of the classification adopted: items whose net saving could not be established were excluded rather than estimated. Had the subscribed-power penalty and the non-costed measures been included, as is often done, the figure would have reached 16.7 %, which is within the usual range.

Two features distinguish this case. The first is the weight of the tariff-structure items. The reactive coefficient and the subscribed-power penalties together represent between 11 % and 14 % of the bill, which is higher than in plants that manage their tariff actively, and is directly linked to the absence of a monitoring function. The second is the low number of equivalent full-load hours, which increases the relative weight of every fixed or quasi-fixed charge. Comparison with the sub-region is limited by the scarcity of published plant-level audits. The available African literature deals mainly with the barriers to industrial energy efficiency rather than with quantified audits. Apeaning and Thollander (17) found, in Ghana's largest industrial area, that the main obstacles are the lack of capital, the lack of technical information and the low priority given to energy management, rather than the absence of technical potential. The present case is consistent with that finding: the largest potential identified is the restoration of an existing installation, which requires organisation rather than investment. Ogunsola and Zwane (18) reach a similar conclusion at the policy level for West Africa. The contribution of this paper is to give a plant-level quantification of that observation. The generator-set analysis also differs from usual practice. Low-load operation of standby sets is widely reported as a cause of degraded efficiency and accelerated wear (10), but the size of the effect is rarely separated from other causes. The decomposition made here shows that low load explains at most one third of the deficit, so the common recommendation to resize standby capacity would address only a minor part of the problem in this installation.

Energy governance and monitoring: The main result of this audit is organisational rather than technical, and it deserves to be stated as such. A compensation system stopped regulating in November 2023 and the loss went unnoticed for fourteen billing periods, although it appears clearly on the monthly invoice. A measurement campaign was carried out with two reversed current transformers, and the fault was found only when the results were analysed. Fuel consumption is recorded, but not against the energy generated in a way that would have revealed the efficiency deficit. In each case the data existed, and what was missing was a routine for reading them.

Four elements of an energy governance framework follow directly from these observations. First, a monthly reading of the billing coefficient with an alarm threshold, which is free and would have detected the largest potential of this study within one month. Second, a verification procedure for the measurement chain before any campaign, including a polarity check on the current transformers, which takes a few minutes on site. Third, a monthly ratio of energy generated to fuel consumed for the generator sets, which turns an isolated audit observation into a permanent indicator. Fourth, a specific energy consumption indicator normalised to production, without which no saving can be verified after implementation. These four elements require no capital investment. They are the precondition for the measures proposed in Section 9 to be maintained over time rather than lost again, as the compensation was.

Limits of the study

The limits are given in decreasing order of importance

L1. The measurement campaign is affected by a polarity fault on two of three current channels and was made on a sub-feeder. No power quantity is derived from it in this paper, but the power-quality characterisation of the plant remains to be established.

L2. No production data were available, so no specific energy consumption could be computed. The plant cannot be compared with sector references, and the interpretation of the 1 959 equivalent full-load hours remains open.

L3. The net saving on the subscribed power could not be established, because the fixed charge per subscribed kW and the peak-demand series were not available. This item is reported but excluded from the total.

L4. The valuation of the reactive potential depends on assumption H2. The range given in Table 7 covers the plausible tariff arrangements, but the actual arrangement should be confirmed with the distributor.

L5. The generator-set fuel law is calibrated on two manufacturer points and is an approximation. Only the

lower bound on the unexplained deficit is robust; the exact coefficients are not.

L6. The capital costs of the solar measures and of the compensation works are estimates and are not supported by quotations. The payback periods should be read accordingly.

L7. The study covers a single site, four years of billing data and one short measurement campaign. The method is transferable but the values are specific to this installation.

Practical implications: Three implications follow. First, the order of the actions matters. Restoring the reactive compensation and clarifying the subscribed-power tariff should come before any investment programme, because together they concern between 11 % and 14 % of the bill at low or no capital cost. Second, monitoring is not an accessory to these measures but their precondition, as Section 10.2 shows. Third, the measurement chain must be verified before any campaign is exploited; in this case a polarity check of a few minutes would have avoided the loss of an entire campaign for quantitative purposes.

CONCLUSION

This paper reports the energy audit of a beverage plant in Sahelian West Africa. The audit is based on four data sources of unequal quality, and its main methodological feature is that each source was assessed before use and each saving potential was classified according to the evidence supporting it. Three potentials are retained, for a total of 6.2 to 8.4 million FCFA per year, that is 7.7 % to 10.5 % of an annual bill of 80.2 million FCFA corresponding to about 685 470 kWh. The largest concerns reactive-energy compensation. The four-year record of the billing coefficient shows that the installation held the best attainable value of 0.920 for eight consecutive months in 2022 and has stayed at exactly 1.000 since November 2023. The target is therefore a capability that was reached and then lost, which is worth 4.2 to 6.4 million FCFA per year depending on the tariff base. A fourth item, the subscribed-power penalty of 4.96 million FCFA per year, is identified but excluded from the total, because the net saving depends on tariff data that were not available; the break-even condition is given instead. For the generator sets, a two-point Willans fuel law shows that low-load operation explains at most one third of the gap between the rated 3.91 kWh/L and the observed 2.20 kWh/L, so at least 1.15 kWh/L comes from another cause and a resizing alone would not correct it.

Finally, a metrological check shows that two of the three current channels of the measurement campaign have reversed polarity and that the campaign was made on a sub-feeder, so all conclusions were re-anchored on the billing records. Two contributions follow. On the substance, the study shows that in this type of installation the dominant potentials lie in the structure of the invoice and in the restoration of existing equipment rather than in new technology, which reverses the order usually assumed in the region. On the method, it shows that an audit should state which of its conclusions depend on the measurement chain and which do not, and it gives a simple procedure for doing so. The priority next steps are: to diagnose and restore the reactive compensation, and to install a monthly alarm on the coefficient; to obtain the tariff schedule and the peak-demand series so that the subscribed power can be optimised; to run a metered load-bank test on the generator sets; to repeat the power-quality campaign at the plant intake after checking the polarity; and to establish a specific energy consumption indicator, without which none of the savings implemented can be verified against production.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Burkina Elite for providing the measurement and analysis equipment used during this energy audit, and for the technical support given throughout the on-site campaign

REFERENCES

Capehart, B. L. W. C. Turner, W. J. Kennedy, Guide to Energy Management, 8th ed., Fairmont Press / CRC Press, Boca Raton, 2016. ISBN 978-1-4987-5933-5. https://doi.org/10.1201/9781003151982

Thumann, A. T. Niehus, W. J. Younger, Handbook of Energy Audits, 9th ed., Fairmont Press / CRC Press, Boca Raton, 2012. ISBN 978-1-4665-6162-5. https://doi.org/10.1201/9781003151722

Patterson, M. G. What is energy efficiency? Concepts, indicators and methodological issues, Energy Policy 24 (5) (1996) 377–390. https://doi.org/10.1016/0301-4215(96)00017-1

International Energy Agency, Energy Efficiency 2023, IEA, Paris, 2023. https://www.iea.org/reports/energy-efficiency-2023

Saidur, R. A review on electrical motors energy use and energy savings, Renewable and Sustainable Energy Reviews 14 (3) (2010) 877–898. https://doi.org/10.101 6/j.rser. 2009.10.018

Trianni, A. E. Cagno, A. De Donatis, A framework to characterize energy efficiency measures, Applied Energy 118 (2014) 207–220. https://doi.org/10.1016/ j.apenergy.2013.12.042

Al Momani, D. Y. Al Turk, M. I. Abuashour, H. M. Khalid, S. M. Muyeen, T. O. Sweidan, Z. Said, M. Hasanuzzaman, Energy saving potential analysis applying factory scale energy audit — a case study of food production, Heliyon 9 (3) (2023) e14216. https://doi.org/10.1016/j.heliyon.2023.e14216

Mahmoud, R. A. E. S. Elwakil, Correlation-based polarity-check algorithm for instrument transformers, Journal of Electrical Systems and Information Technology 11 (2024) 49. https://doi.org/10.1186/s43067-024-00172-y

Lawrence, A. P. Thollander, M. Andrei, M. Karlsson, Specific energy consumption/use (SEC) in energy management for improving energy efficiency in industry: meaning, usage and differences, Energies 12 (2) (2019) 247. https://doi.org/10.3390/en12020247

Issa, M. H. Ibrahim, R. Lepage, A. Ilinca, A review and comparison on recent optimization methodologies for diesel engines and diesel power generators, Journal of Power and Energy Engineering 7 (6) (2019) 31–56. https://doi.org/10.4236/jpee.2019.76003

Jenkins, N. J. B. Ekanayake, G. Strbac, Distributed Generation, IET Renewable Energy Series 1, The Institution of Engineering and Technology, London, 2010. ISBN 978-0-86341-958-4. https://doi.org/10.1049/PBRN001E

Pepermans, G. J. Driesen, D. Haeseldonckx, R. Belmans, W. D'haeseleer, Distributed generation: definition, benefits

and issues, Energy Policy 33 (6) (2005) 787–798. https://doi.org/10.1016/j.enpol.2003.10.004

Evans, J. A. A. J. Gigiel, Reducing energy consumption in cold storage rooms, in: Proceedings of the 1st IIR International Cold Chain Conference, Cambridge, United Kingdom, 29–31 March 2010, International Institute of Refrigeration, Paris, 2010.

Foster, A. M. L. Reinholdt, T. Brown, E. C. Hammond, et al., Reducing energy consumption in cold stores using a freely available mathematical model, Sustainable Cities and Society 21 (2016). https://doi.org/10.1016/ j.scs.2015.11.006

Tassou, S. A. Y. Ge, A. Hadawey, D. Marriott, Energy consumption and conservation in food retailing, Applied Thermal Engineering 31 (2–3) (2011) 147–156. https://doi.org/10.1016/j.applthermaleng.2010.08.023

Bollen, M. H. J. Understanding Power Quality Problems: Voltage Sags and Interruptions, Wiley-IEEE Press, New York, 2000. ISBN 978-0-7803-4713-7.

****