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ENERGY BUDGETING AND CONTROL FOR INDUSTRIAL PLANT THROUGH CONSUMPTION ANALYSIS AND MONITORING

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ABSTRACT
The purpose of this paper is to provide a method for planning and control of electrical energy budget for an industrial plant. The authors propose a methodology that approaches effectiveness and efficiency of budget estimation based on energy consumption forecast and control and energy price analysis.

The methods aims to obtain a very high confidence of predicted electrical energy cost to include into the estimation of budget and a continuous control of energy consumption and cost.

The methodology is based on tools already used in other sectors as statistical control of production processes, market demand forecast and budget planning and control in project management.

Authors show the methodology in detail through practical application to a case study of an industrial plant with the 20% incidence of electrical energetic cost on the final product.

KEY WORDS
Energy budgeting, energy consumption, CUSUM

1. Introduction

Industries are paying more attention to energy budgeting and control due to the growing cost of energy. One of the most difficult problems which many energy managers face is to justify energetic budget in order to cover energy cost and invest money on increasing its energy efficiency, especially when there are other, seemingly more important priorities for the use of its capital. Organization typically give priority to invest in what they see as their core or profit-making activities instead of energy efficiency. Also when they do invest in energy saving, they tend to demand faster rates of return than required from other kinds of investment [1] .

Energy budgeting has became a priority of "energy management" discipline. In particular industries needs estimation of energy budget with high confidence. The authors provide a method for planning and control of energy budget for an industrial plant. This paper shows a methodology that could support an organization to each efficiency of budget estimation and, at the same time, to build up a system for a continuous reduction of energy costs through:

- forecast, monitor and control energy consumption
- analyse the energy price related to different kind of energy tariff.

In literature specific methods exist as review in [2]. For example methods based on use time series analysis or autoregression are used to support energy forecast and budgeting but doesn't allow to correlate the energy cost to several factors influencing energy consumption [3]. So this kind of techniques supports to reach a specific objective but not a complete analysis.

By this point of view, the aim of this paper is to propose a method that exceeds the previous limits and permit to consider the variables related to energy consumption forecast and to deeply monitor energy budgeting. The authors propose a new technique for energy budgeting and control based on earned value technique used in project management [6] that support both budgeting and control.

Authors show the methodology in detail through practical application to a case study of an industrial plant for plastic production with the 20% incidence of electrical energetic cost on the final product.

2. Methodology

The proposed methodology follows four steps:
1. energy consumption characterization: developing a prediction model of the energy use from past energy consumption data;
2 energy consumption forecasting: using the previous result to forecast energy consumption for the next period based on forecasting of production, and if necessary of the other energy drivers;
3. tariff analysis: understanding energy cost in function of energy load and tariffs for time bands; choosing the best energy tariffs for contract renewal based on forecast of energy consumption;
4. energy budgeting and control: defining forecast baseline for provisional budget relating to each cost centre and monitoring through indicators.

2.1 Energy consumption characterization

First of all it is necessary to understand the historical consumption process in order to foresee consumption, The type of consumption process could be generally divided into:

- process with energy utilization is define from a physical point (i.e heating, evaporation, cooling, compression): they are regular and easily to characterized;
- process with not stable energy consumption (i.e. mechanical operation, mixture, transport): it could be necessary identify a meaningful relation energy consumption and production variables.

In the second case a mathematic model could be defined to describe the relation between energy cost/consumption and energy drivers (factors that make sensible process to variation) [4]. In particular this way has to be followed if the measurement system is defined by higher level than single physical process.

The first step is the characterization of the system through identification of energy drivers. Energy drivers depend on the systems. For example:

- production volume or differences for electrical energy for motive power;
- sunlight variation for electrical energy for lighting;
- degree day for electrical energy for heating.

Therefore the consumption of energy has to be defined with the expression in (1):

$$C(\alpha,\beta,\ldots) = E_0 + f(\alpha) + f(\beta) + \cdots \qquad (1)$$

where α, β are the energy drivers.

The expression could be calculated by a multiple regression between energy drivers and consumption.

In order to perform the regression it is necessary to gather data about consumption and energy drivers. For consumption it is possible to refer to data from equipment as electrical meters. For energy drivers it is necessary to access to the company available databases.

Data could be not homogeneous and it could be necessary controlling before start with analysis. Energy drivers reliable has to be assess with statistical analysis. In this way, we could foresee the consumption from the different energy drivers based on statistical model. Moreover this characterization should be used to control energy consumption process with CUSUM chart that stands for the cumulative sum of differences. The differences added are those between the actual energy used and the energy predicted. The CUSUM control chart indicates the data for the immediate previous week and its difference and points out a difference in consumption process. Referring to [5] to deal with this topic exhaustively.

2.2 Energy consumption forecasting

Since the model step has been completed we can use it to calculate the consumption forecast for the next periods based on reliable energy drivers.

Therefore energy drivers value has to be included in the model equation to obtain the electrical energy consumption forecasting. For instance, in order to identify:

- Production: we could refer to companies production plan or demand forecast;
- Sunlight variation: we could refer to meteorology web-sites or databases;
- Degree day for electrical energy for heating we could refer to a mean value obtained by the past years.

2.3 Tariff analysis

Analysis of energy price has to be done in order to reach efficiency of budget estimation. In particular tariff analysis is powerful during contract renewal. In this case it is necessary:

- choosing the less expensive solution relating to own forecasted energy load profile ;
- considering the impact of the different contractual options on the unit energy cost.

It is necessary to consider the different factors that affect energy tariff in order to compare all options with homogenous criteria. For example electrical energy tariff could be influenced by total consumption, power furniture, voltage, time bands (tb), customer forecasting capability, and fuel price.

The previous factors differs among offers (f1,f2,..,fn) and has to be considered during contract renewal to determine the best one fopt minimizing the cost applied to energy consumption forecast C(á,â,...) as shown in the expression in (2):

$$f_{opt}(t) = \min_{i\varepsilon\{1,\ldots n\}} \left[f_i(t) x C(\alpha,\beta,\ldots) \right] \qquad (2)$$

Moreover we could understand formation of total cost through analysis of energy price relating to hourly unit energy cost.

2.4 Energy budgeting and control

The authors propose a new technique for energy budgeting and control based on earned value technique used in project management [6].

At this point is useful to distinguish two substeps: budgeting and control.

For budgeting we has to calculate energy consumption as from the results of the consumption forecasting and the best tariff options.

Referring to the previous expressions, the budget cost (BC) can be calculated as in (3):

$$BC(t,\alpha,\beta,\ldots) = f_{opt}(t) \quad x \quad C(\alpha,\beta,\ldots) \qquad (3)$$

The next indicator has been defined:

- Budget Cost of Energy for Scheduled energy drivers (BCES): the cumulative sum of the monthly energy cost calculated as from the results of the consumption characterization and the chosen tariff; the BCES at the end of the year is the budget to attribute in the budget plan.

For controlling we has to determine the differences between BCES and actual cost. The next indicators have been defined:

- Actual Cost of Energy for Actual energy drivers (ACEA): the cumulative sum of the energy monthly costs really sustained by the company relating to the actual energy drivers;
- Budget Cost of Energy for Actual energy drivers (BCEA): the cumulative sum of the monthly energy cost calculated inserting the actual energy drivers in the energy consumption model, considering time subdivision of the chosen tariff.

Basing the study on these indicators it is possible to deeply investigate on the company energetic behaviour related to the selected energy drivers. It is possible to point out the next cases:

- ACEA > BCES: this situation means the company has spent more than predicted; for instance if the energy driver selected were production this situation should depend by a difference between actual and planned production (for quantities or mix) and/or an higher specific consumption . In order to distinguish this two cases we have to consider the following condition:
  - ACEA > BCEA means an higher specific consumption for unit production for the same amount of energy drivers; it is important to analyze the energetic behaviour in terms of ACEA and BCEA for each production department, and in terms of KPI for the department that reveal a behaviour classified as out of prediction;
  - BCEA > BCES means different energy drivers than predicted, assuming the consumption model obtained from regression completely reliable; it is important to analyze the difference between the actual and scheduled of energy drivers both in quantities and in time subdivision.

In conclusion we should separate the contribution due to inefficiency of consumption (ACEA – BCEA) and due to different energy drivers scheduling (BCEA – BCES). The budget to attribute in the budget plan has to be re-planned.

3. Case of study

The company we have considered in this work is involved in production of plastic materials for packaging. The electricity used in the plant is entirely supplied by the electric network: the energy is provided to the main patch box, that has a power of 1500 kW installed. Here we have both the company and the provider electricity meter. From here the energy is sent to the main production sectors: the plastic material and the aluminum production departments. The first basically uses the 70% of the incoming energy, the second the resting 30 %. For this reason the energetic policy of this company has led to improve the electricity metering in the first area. This production department is characterized by eight different units. Each unit is controlled with his own meter, that measures the energy consumption due to the machines, with a 15 minutes resolution. The plant work is scheduled in three daily turns, for a total consumption of 12000 MWh in the 2005. The structure of the electrical meters tree is shown in fig. 1

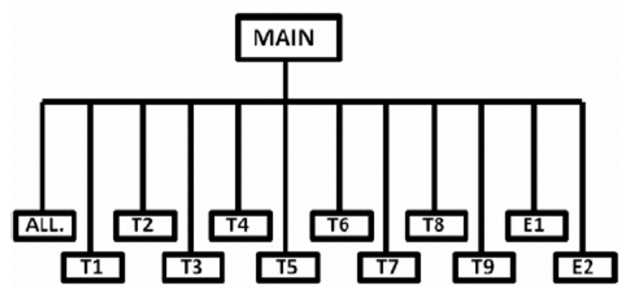


Fig. 1 Electricity meters tree

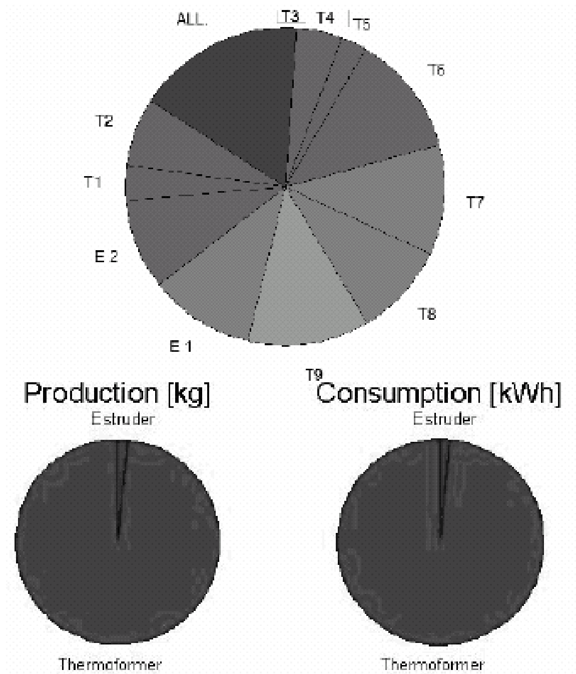
The aim of this work is to build up a reliable energy budget prevision through consumption modeling and cost analysis. The model is realized relating the detailed consumption data to production data.

The plant produces several different products, classified by shape and size, and identified by a specific tag. Basically seventy different types are distributed among different areas.

The production dataset records the production by unit, day, machine, turn, and amount of product in kilogram, specifying for each turn the starting and end time (that are not always the same).

Characterization needs to understand the effective distribution of the energy consumption among all the electrical meters.

In fig.2 we can see the total energy amount shared between different sites for all the 2005. Going deeply in the analysis the situation described in fig.3 can be observed: almost the total consumption and production can be related to thermoformer, while the extruders are involved in the process only for less than 2 per cent. This allow to negligee the extruder for each site and concentrate the method on the other machine. An important hypothesis is to consider all the consumption entirely related to production, ignoring the presence of service like lighting and heating, assuming that amount to be constant in the time, and not important in the analysis of variance.



Figg 2-3 Distribution of energy consumption between sites(2) and machines inside a department (3).

The model is based on correlation and regression between consumption and production data isolated for each product with working turn time resolution. The fifteen minutes detail of electric measure is lost to accomplish the match between the energy consumption and its energy driver, the production. In this way for each product is possible to obtain a correlation value. For correlation value higher than 0.8 and prediction error lower than 0.12 we consider the regression reliable.

The model has been validated with statistical technique of F-test for regression and T-test for coefficients. For each product the difference between the real consumption and the predicted consumption was cumulated and controlled statistically [7]. An example of regression analysis has shown in table 1.

The report shows correlation and determination coefficient R and R^2. Radj is the determination coefficient weighted on the degree of freedom of the regression. The residual analysis has been performed to verify the normality hypothesis The statistical report includes Standard Error and number of observation. The coefficient validation has been tested with the student test at 95% confidence. Each coefficient is reliable for a linear relation for a P-Value lower than 0.05.

The equation calculated by regression for unit 1 is show as an example in (4):

$$
\begin{aligned}
&C(P_1, P_2, \ldots P_5) = E_0 + f(P_1) + f(P_2) + \ldots + f(P_5) \\
&C(kWh) = 56{,}2\,kWh + 0{,}43\,kWh/u \;\; x \;\; P_1(u) + \\
&+ 0{,}36kWh/u \;\; x \;\; P_2(u) + 0{,}27kWh/u \;\; x \;\; P_3(u) + \\
&+ 0{,}42kWh/u \;\; x \;\; P_4(u) + 0{,}45kWh/u \;\; x \;\; P_5(u)
\end{aligned}
\quad (4)
$$

The budget is calculated summing he result of the regression equation for each site, along each month. An important feature that comes out from the analysis of the past is the weight that each product assumes on both the energy consumption and the production. Visualizing pie charts as the one showed in fig. 4a it is possible to immediately understand where is important to refine the model, and how can be simple to identify an inefficient behaviour.

Table 1. Statistical report for regression on department 1.

	R	0.82556		
	R2	0.68154		
	Radj	0.66616		
	Stand. Error	4.822.921		
	N	218		
Coefficients	Value	Standard error	T-value	P-value
Quote	56,2	70,5	7,3	0,0005
Prod1	0,43	0,05	8.12	0,0003
Prod2	0,36	0,04	8,32	0,0001
Prod3	0,27	0,11	2,32	0,0002
Prod4	0,42	0,027	12,56	0,0007
Prod5	0,45	0,04	10,44	0,0008

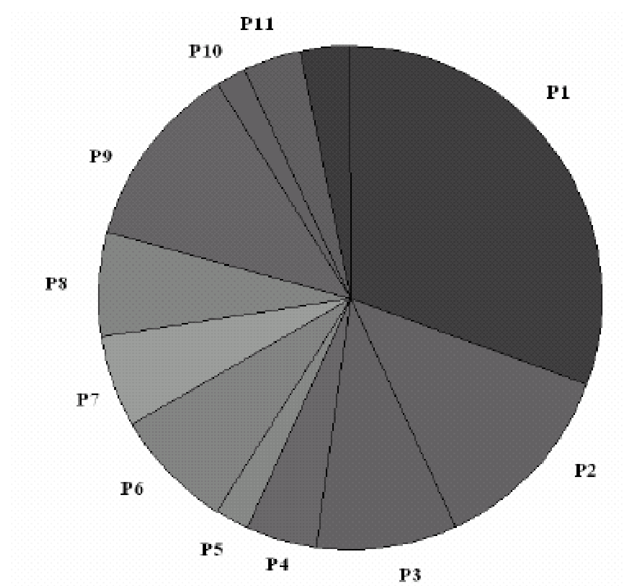


Fig.4a Consumption (kWh) of products for unit 2

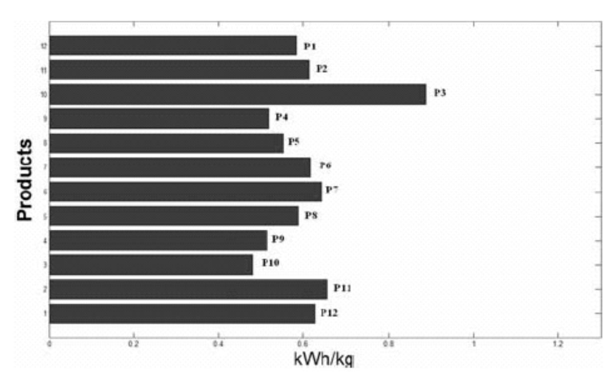


Fig.4b KPI (kWh/kg) of all products for unit 2

The Key Performance Indicators (KPI) are calculated as consumption divided by the relative production for each product. So even if the KPI increases for P3, the most energetic product, it is more important to monitor the P2, because of the percentage in the real production. The KPI level is a fundamental device to find the problem in a complex production system. Since the characterization step has been completed we can use the model to calculate the energy budget plan for the first trimester of the following year.

At the time of the contract renewal the company has decided to compare different Italian providers proposals. In order to identify the lower cost the energy consumption profile predicted for the next year (2007) has been considered. The energy consumption has been calculated including the production prevision for the 2007.

The study of tariffs can be concentrated on two types: the fixed tariff, and the variable tariff. Each tariff defines the energy cost related to different periods of the day.

In this case of study five fixed proposals, three based on two daily periods (peak-off-peak), the other three based on three daily period (F1, F2, F3) are presented. So the specific energy cost can be calculated as in (5):

$$f(t)=P_0(t) \qquad (5)$$

where n is related to the month of energy collection and P0 is a fixed parameter for each period.

The other seven proposals have a tariff dependent on the fuel costs as in (6):

$$f(t)=P_0(t) + (I_n(t) - I_0(t)) \qquad (6)$$

where Io(t) is a fixed coefficient in function of time bands, In(t) is a coefficient related to the specific month and based on the variation of fuel prices on different periods. To compare the different costs we have calculated the kWh specific cost for each daily period of the tariff. The costs have been applied for each month to consumption profile of the company to figure out a mean cost for each month.

The best tariff returned is a two daily period fixed tariff with a cost of 10,24 €cent/kWh for peak period e 4,93 €cent/kWh for off-peak period. Once the tariff is chosen we can calculate the energy budget plan for the first trimester, compare the different indicators for all the period and visualize the results for each site (fig 5-6). For the 2007 only the BCES can be plotted. The other two indicators depend on energy cost (ACEA) and actual production value (BCEA). In figure 6 the distribution among areas can be visualized. It is possible to observe as T7 and T8 are two of the most expensive area according to fig. 1. Respect to 2006 the departments T4 and T5 has been powered in their production activity.

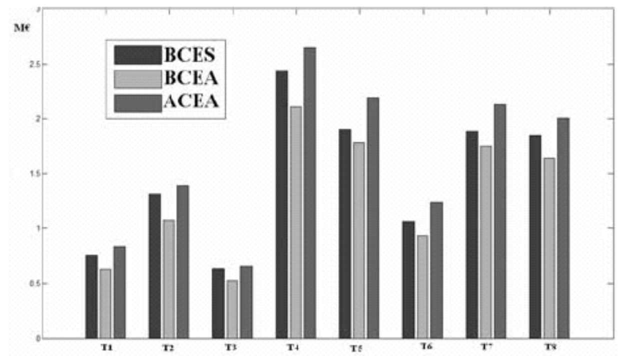


Fig.5 Budget control for the eight departments

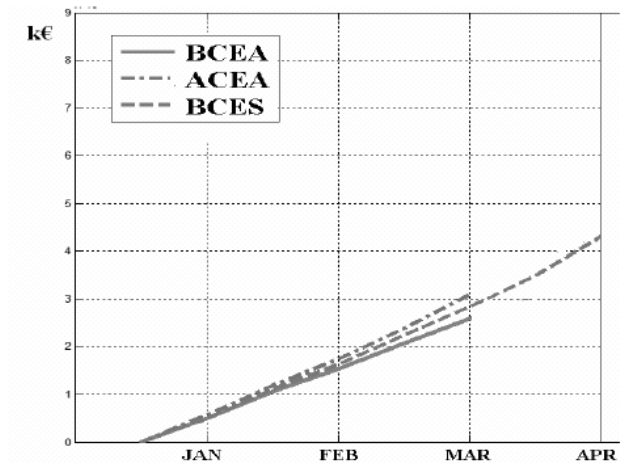


Fig.6 Cumulative indicators for budget control

We can observe the same situation at the end of the first three months:

- The actual Energy costs are higher than scheduled (ACEA>BCES): it means a negative budget situation. This trend is sending budget out of control. To investigate the reasons it is necessary to analyze the other two indicators.
- BCEA<BCES: the production is lower than scheduled, or the product mix is different.
- BCEA<ACEA: the energy spent is higher than scheduled by the model with the actual amount products realized so that the specific consumption has increased.

At this point we can say that the company activity is strongly inefficient: with this volume of production the budget should be under control, because it expected to be lower than scheduled. Going deeply in the analysis, studying graphs as the one shown in fig. 7, the reason of the difference comes out. For example the product P3 from the site 2 had an absorption of 0.685 kWh/kg in the past, while this value has now increased to 0.865 kWh/kg. This conclusion couldn’t be obtained before with a traditional total KPI 0,815 kWh/kg (total consumption on total production). The goal is to justify this inefficiency by a technical point of view. Considering that it occupies almost the 17% of the site total consumption it is clear how this unbalance weights on the costs and on the efficiency of the production of the area T2.

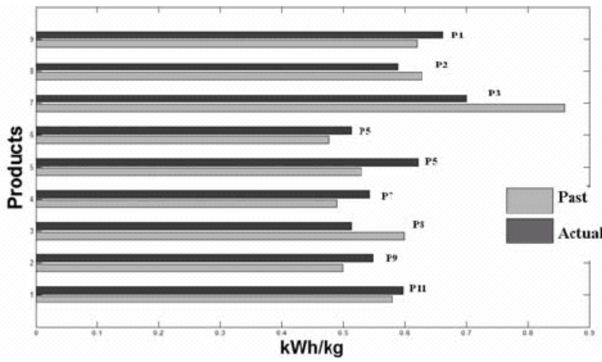


Fig. 7 Comparing KPI of all products for site 2

The indicators permits to visualize the situation by a general point of view. Performing the analysis through Key Performance Indicators of the examined period compared to historical, it is possible to determine dangerous factors. The energy manager is allowed to identify the reasons of this negative budget difference.

Getting through to the different units it is possible to understand if the malfunctioning can be fixed or it is necessary to take in account the higher specific consumption. In this case of study an higher specific consumption occurred so in budget re-planning it had been considered. The new budget has been formulated considering specific consumption of production mix. In this case the total budget plan was 10% more accurate than in a static and classic formulation, based on the global consumption related to the total production without any differentiation.

In both analyzed cases utilizing the model it is possible to plan a new budget cost: if the problem can be fixed the model coefficients are still valid and it is only necessary to include the difference (ACEA – BCEA); if not, the model needs to be modified with the actual specific consumption for unit of product volume. On the production side it is possible to profile an updated volume of production, observing that the production is on late (BCEA<BCES).

The results permits to analyze the production in terms of efficiency and respect of budget plan. The data offers different level of detail, according to different situations.

In this case of study the energy related to production is an available data, thanking to the detailed electrical energy metering system installed in production departments. The multilinear regression is based on analysis of variance between input and output, so for each period it is possible to consider the amount energy spent in lighting or cooling as a constant or absent contribution. The limitation in the case of study is the application of the forecast method and regression only to production machine where the energy drivers are limited to the production volume. A future development could be the application also to support service equipment of the entire industrial plant.

4. Conclusion

A method for planning and control of electrical energy budget for an industrial plant has been performed. The application shows the effectiveness to obtain energy cost to include into budget planning and control. The method can be applied only if a detailed metering system is already present. The more the metering system is developed, the more the result performed is reliable. A previous study is necessary on each unit to identify the energy driver to correlate to consumption. The analysis can be performed in other cases considering other energy drivers as temperature, relative humidity, turns, darklight variability during the solar year. It depends on the activity related to metered unit. The choice of energy drivers, at the moment of collecting data, is managed by assumptions that the energy manager does for each unit. An hypothesis valid for a unit or a company can result weak and unreal for another, limiting the power of fast characterization, and requiring other kind of constrains. For instance, the characterization could be differentiated seasonally, by semester or yearly. After modelling the elements included have to be statistically validated.

The aim of this method is to show how a good level of control can be reached with a little dataset and simple statistical algorithm application. It is necessary to remember that the higher is the number of energy drivers included, the higher is the error. In addition, as seen before, all the time resolution of the analysis will be adapted to the slower data. The energy budget control can be simply performed with statistical characterization and control techniques, but every situation needs its own assumptions and validations.

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