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Methodology Development for a Comprehensive and Cost-Effective Energy Management in Industrial Plants

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1. Introduction

Energy management can be defined as "the judicious and effective use of energy to maximise profits and to enhance competitive positions through organisational measures and optimisation of energy efficiency in the process " (Cape, 1997). Profits maximization can be also achieved with a cost reduction paying attention to the energy costs during each productive phase (in general the three most important operational costs are those for materials, labour and electrical and thermal energy) (Demirbas, 2001). Moreover, the improvement of competitiveness is not limited to the reduction of sensible costs, but can be achieved also with an opportune management of energy costs which can increase the flexibility and compliance to the changes of market and international environmental regulations (Barbiroli, 1996). Energy management is a well structured process that is both technical and managerial in nature. Using techniques and principles from both fields, energy management monitors, records, investigates, analyzes, changes, and controls energy using systems within the organization. It should guarantee that these systems are supplied with all the energy that they need as efficiently as possible, at the time and in the form they need and at the lowest possible cost (Petrecca, 1992).

A comprehensive energy management programme is not purely technical, and its introduction also implies a new management discipline. It is multidisciplinary in nature, and it combines the skills of engineering, management and maintenance. In literature there are many authors that approaching the different aspects of energy management in industries. For sake of simplicity, identifying the main issues of the energy management procedure in energy prices, energy monitoring, energy control and power systems optimal management and design, in Table 1, for every branch the most significant scientific results are listed.

Concerning energy price in the new competitive environment due to the energy markets liberalization, many authors face up the risks emerged for market participants, on either side of the market, unknown in the previous regulated area. Long-term contracts, like futures or forwards, traded at power exchanges and bilaterally over-the-counter, allow for price risk management by effectively locking in a fixed price and therefore avoiding

uncertain future spot prices. In fact, electricity spot prices are characterised by high volatility and occasional spikes (Cesarotti et al., 2007), (Skantze et al., 2000), (Weron, 2008). Moreover finding the best tariff for an industrial plant presents great difficulties, in particular due to the necessity of a predictive consumption model for adapting the bids to the real consumption trends of the plants.

Energy management Areas	Main Issues	Bibliography
Energy costs	Forecasting price of energy Renewal of contracts	(Cesarotti et al., 2007), (Skantze et al., 2000), (Weron, 2008)
Energy budgeting	Forecasting consumption Monitoring and analyzing deviations from the energy budget	(Farla & Blok, 2000), (Worrel at al., 1997), (Kannan & Boie, 2003), (Cesarotti et al., 2009)
Energy consumption control	Design and implementing monitoring system Forecasting and control consumption of specific users	(Brandemuel & Braun, 1999), (Elovitz, 1995), (Krakow et al., 2000), (Di Silvio et al., 2007)
Optimization of power systems	Defining the equipments optimal set points Increasing the overall system efficiency	(Sarimveis et al., 2003), (Arivalgan et al., 2000), (Von Spakovsky et al., 1995), (Frangopoulos et al., 1996), (Puttgen & MacGregor, 1996), (Tstsaronis & Winhold, 1985), (Temir & Bilge, 2004), (Tstsaronis & Pisa, 1994)

Table 1. Energy management open issues

Several studies on energy monitoring by using physical indicators to analyse energy efficiency developments in the manufacturing industry (especially the energy-intensive manufacturing industry) highlight the close relationship with the concept of specific energy consumption (energy use at the process level) and the international comparability of the resulting energy efficiency indicators as arguments advocating the use of physical indicators in the manufacturing industry (Farla & Blok, 2000), (Worrel at al., 1997). Moreover in (Kannan & Boie, 2003) the authors illustrate the methodology of energy management that was introduced in a German bakery with a clear and consistent path toward introducing energy management. Finally in (Cesarotti et al., 2009) the authors provide a method for planning and controlling energy budgets for an industrial plant. The developed method 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 energy control for specific systems is mainly focused on implementing one energy management control function at a time with or without optimal control algorithms (Brandemuel & Braun, 1999), (Elovitz, 1995), (Krakow et al., 2000). In (Di Silvio et al., 2007) a method for condition-based preventive maintenance based on energy monitoring and

control system is proposed. The methodology supports to identify maintenance condition through energy consumption characterization, predicting and control (Cesarotti et al., 2010). In (Sarimveis et al., 2003) an example of power systems management optimization through mathematical programming tools is presented. In other terms, the availability of optimization tools for the energy plant operation (i.e. the possibility of optimally determining when boilers, turbines, chillers or other types of machinery shall be set on or off or partialized) may lead to energetic, economic and environmental savings. In scientific literature, several criteria for the optimization of combined cooling, heating and power systems in industrial plants are available based on different management hypotheses and objective functions. The goal of the models is to optimize the operation of the energy system to maximize the return on invested capital. Many of these models do account for load operations but use simple linear relationships to describe thermodynamic and heat transfer process that can be inherently non-linear. In (Arivalgan et al., 2000) a mixed-integer linear programming model to optimize the operation of a paper mill is presented. It is demonstrated that the model provides the methods for determining the optimal strategy that minimize the overall cost of energy for the process industry. In (Von Spakovsky et al., 1995) the authors use a mixed integer linear programming approach which balances the competing costs of operation and minimizes these costs subject to the operational constraints placed on the system. The main issue of the model is the capability to predict the best operating strategy for any given day. Nevertheless, the model validity is strictly dependent on the linear behaviour of the plant components. In (Frangopoulos et al., 1996) the authors have employed linear programming techniques to develop an optimization procedure of the energy system supported by a thermoeconomic analysis of the system and modelling of the main components performance. In (Puttgen & MacGregor, 1996) a linear programming based model maximizing the total revenue subject to constraints due to conservation of mass, thermal storage restrictions and shiftable loads requirement is developed. Finally, thermoeconomics offers the most comprehensive theoretical approach to the analysis of energy systems where costs are concerned. It is based on the assumption that exergy is the only rational basis to assign cost. In other terms, the main issue is that costs occur and are directly related to the irreversibility taking place within each component. Accordingly thermoeconomics could represent a reliable approach to the optimisation of energy plants operation involving thermodynamic and economical aspects (Tstsaronis & Winhold, 1985), (Temir & Bilge, 2004), (Tstsaronis & Pisa, 1994). However, these studies have paid little attention in integrating the different individual energy management functions into one overall system. From this point of view, in this chapter we provide a comprehensive integrated methodology for implementing an automated energy management in an industrial plant.

2. Background and motivation

In the last decade, energy management has undergone distinct phases representing different approaches (Piper, 2000):

- Quick fixes: facing with rapidly escalating costs and the prospect of closings resulting from energy shortages, facility managers responded by implementing a round of energy conservation measures.
- Energy projects: once a fairly wide range of quick fixes had been implemented, facility managers came to realize that additional savings would require the implementation of

energy conservation activities, which are expensive and time-consuming. The emphasis shifted from quick fixes to energy projects.

- Energy management system: to fight these rising costs, organizations developed more comprehensive approaches to energy management moving from simply reducing energy consumption to managing energy use.

Organizations (both national governments and industrial companies) are recognizing the value and the need of energy management. If they are to be successful, they must understand what worked in the past and why, and what did not work and why it failed. In the last few years, some energy management models have been developed inspired by quality and environment management systems (ISO 9001). For this purpose, in 2005, the ANSI set up and published the first regulation concerning energy management system: the MSE (management system for energy), published by the American National Standard Institute. The objective of this standard is the definition of a reliable model which can be used in different scenarios, to promote the reduction of the energy costs/product unit ratio. The model/standard has to manage all kind of energy costs, in each step of the energy supply chain: supply, transformation, delivery and use. In other words, the application of this standard means setting up programs to manage energy use, instead of randomly funding energy saving projects. In this scenario the energy saving should be performed through a systematic approach operating on energy costs, energy budget preparation, measure and control of power consumption and energy production and conversion. Energy saving can be, in fact, realized through different actions on both the utilization and the production sides. However, it is really a complex task as many factors influence energy usage, conversion and consumptions. Moreover, these factors are strictly interconnected. For example, when evaluating an action on the energy consumption/production, one should take care of the interactions, as one measure influences the saving effect of the other measures. Therefore, it is important to highlight that each element of this systematic approach is strictly connected to the others, as explained in the following.

First of all in the process of renewing the energy supply contract, it is necessary to compare several rate proposals, as in the electricity and fuel market there are a number of different suppliers. This comparison is quite difficult for two reasons. Firstly, the energy rate depends on numerous factors and is usually made up of many different voices. Secondly, although the rate per kWh may be disguised in the electric bill, it varies in function of time and/or power request. This means that the consumption profile has to be known in order to make a prevision on what one is going to pay.

As making this consumption profile on historical data may lead to wrong predictions and non-economic actions and, considering that the annual energy cost is significantly affected by the chosen rate, an energy consumption model should be built. This means modeling the industrial plant energy consumption in function of its major affecting factors (i.e. energy drivers), as production volume, temperature, daylight length etc. This model should give the expected consumption in function of time and the time-step should be as small as possible in order to have reliable predictions. By this way it could be possible to distinguish the plant consumption and the energy drivers variation within the time bands of the energy rate. This could be done by installing a measuring system to record energy consumption and energy drivers. The meters position within the plant is particularly important to correlate the energy consumption to the energy drivers (i.e. different production lines). Therefore, a preliminary analysis based, for example, on the nominal power and the utilization factor of the single machines should be performed in order to build a meters tree.

A reliable energy budget formulation is needed, not only as a part of the whole plant budget, but also to define possible future investments on the energy sector. The present methodology allows to build the energy budget on the predicted energy profile and not only on the historical data basis, as usually done, thus taking into account the possible variation of the energy drivers and of the energy price. The latter could be optimized as described in the previous paragraph and correlated to indexes, as for example the oil market price. Moreover, if an energy system is present in the plant, the budget could not be built on the basis of the previous consumption profile, as the quantity of electricity drawn from the public network could vary as the self-production varies in function of the utilization of the energy system itself (i.e. the optimization of the energy system management as a part of the present methodology).

As far as the possible investments on energy saving are concerned, a correct measure and control of energy consumption is crucial. First of all the energy use measurement alone is not enough, as the predictive model requires correlating energy consumption with several energy drivers that should be accurately and frequently collected, making different measures in different plant areas. This would allow, in fact, to better correlate the consumption to the production on one hand and to undertake energy saving operations specifically designed in each zone on the other. Besides, it is worth to note that the predicted consumption should be compared to reference values in order to understand if the industrial plant is efficient or not.

Finally, an optimal energy management methodology should take into account the management of the energy system machines of the industrial plant, which means setting the load of the energy conversion equipments (i.e. boilers, air-conditioning systems and refrigerators, thermal engines) that optimizes energy cost with a given energy consumption profile (both electrical and thermal). Usually these small energy systems are operated simply switching on and off the machines for long time intervals (i.e. night and day, winter and summer). However, the machines typically used in these systems have small thermal inertia, thus allowing quick load variation, and may be operated under partial load. As demonstrated by the authors in (Andreassi et al., 2009), the energy system model together with the energy consumption one may lead to an optimal management of the power plant thus reducing energy costs. This, again requires a detailed energy consumption profile and then an accurate data collection system.

Besides, on the wake of the previous models, the CEN-CENELEC elaborated the EN 16001, published in July 2009, with the reference standards for the Energy Management System. The rule covers the phases of purchasing, storing and use of the energy resources in different type of organizations (industrial, commercial, tertiary). As the ISO 9001 and ISO 14001, the rule is based on Deming Cycle and the Plan-Do-Check-Act approach.

The EN 16001 has the aim of specifying the requirements of an Energy Management System. The adoption and the maintaining of this standard demonstrates a concrete commitment for the rationalization and the “intelligent” management of the energy resources.

Moreover the ISO Project Committee ISO/PC242 is working to publish an International Standard for Energy Management named ISO 50001. Probably this will be the more important standard for Energy Management for the next years. By now the final version of ISO 50001 is due to be released in the third quarter 2011.

Starting from these critical issues, in this chapter, a methodology considering energy management in a comprehensive manner is provided. A method for energy efficiency based on a systematic approach for energy consumption/cost reduction, which could

simultaneously keep into proper account all the critical aspects just pointed out, is proposed.

3. Methodology for a comprehensive energy management

The methodology framework is shown in Figure 1. The single steps have been discussed in detail by the authors in previous papers (Cesarotti et al., 2007), (Cesarotti et al., 2009), (Di Silvio et al., 2007), (Andreassi et al., 2009). In this chapter the whole methodology and the importance of links and interconnections among the different phases and their role in reducing costs are highlighted.

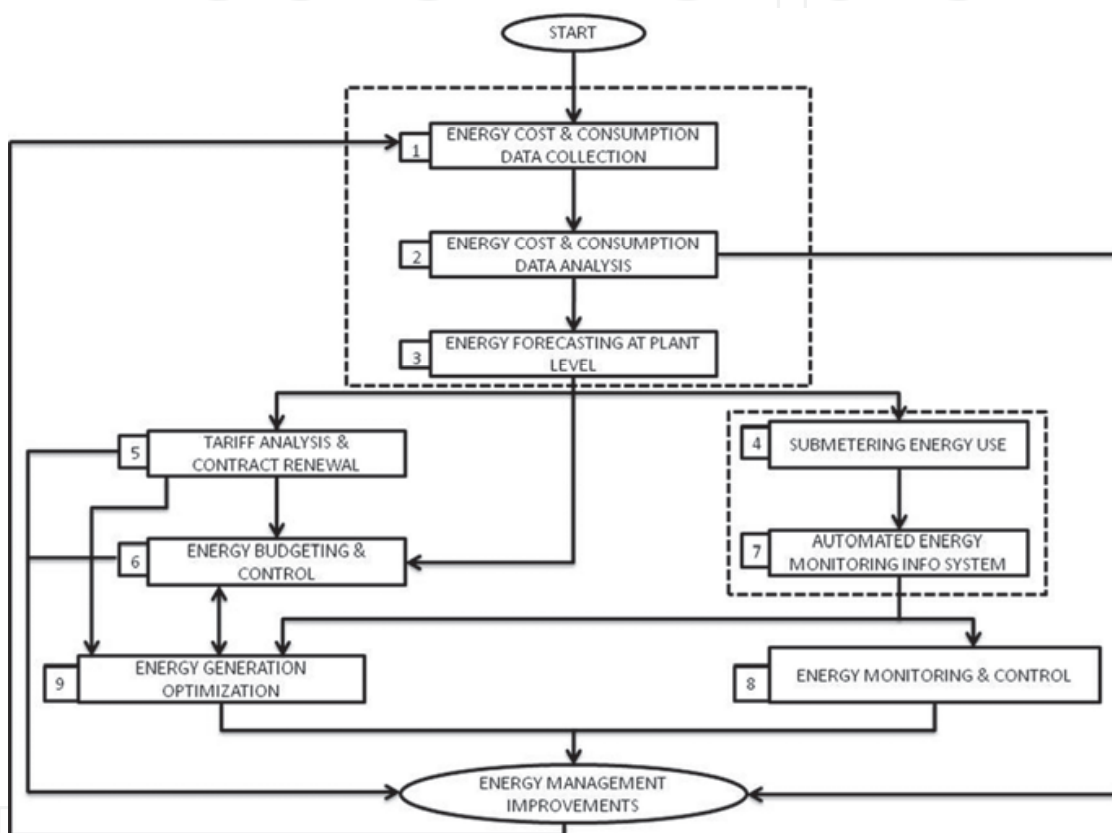


Fig. 1. Framework of the proposed methodology for Energy Management improvements

The main issues of the proposed methodology are: historical data analysis, energy consumption characterization, energy consumption forecasting, energy consumption control, energy budgeting and energy machines management optimization. The methodology supports an industrial plant to:

- identify areas of energy wastage - for example by determining the proportion of energy that does not directly contribute to production and that is often a source of energy savings;
- understand energy consumption of the processes - by establishing a relationship between energy use and production;
- highlight changes to energy consumption patterns - these are either a result of a specific action to improve efficiency or due to an unknown factor which may have a detrimental effect upon efficiency and may lead to process failure or poor quality product;

- identify sporadic faults or events - by alerting operators if excursions from normal, or predicted, production performance are observed;
- reach an optimal condition in terms of supplying, generation, distribution and utilization of energy in a plant by means of a continuous improvement approach based on energy action cost- benefit evaluation.

The single operation described in the methodology steps has its own effectiveness in a context showing an awareness lack about energy management concept. Nevertheless, our intent is to point out the importance of introducing each step in a non-ending loop, granting continuous energy management improvements and a constant reduction of energy consumptions and costs.

Accordingly, in the following sections each step characterizing the proposed methodology will be described in detail. The different phases are:

- energy cost & consumption data collection;
- energy cost & consumption data analysis;
- energy forecasting at plant level;
- sub-metering energy use;
- tariff analysis and contract renewal;
- energy budgeting and control;
- energy monitoring and control;
- power plant management optimization;

Every step is deeply analyzed in the successive paragraph and an application of each of these steps is shown in the case study of the paragraph 6: this working example will support the explanation of the various aspects of the developed methodology.

4. Description of the methodology steps

4.1 Energy cost & consumption data collection

The first step consists in collecting useful data for characterizing the energy consumptions of an industrial plant. We can essentially distinguish four types of variables which can be collected:

- consumption data;
- production data;
- environmental data;
- technical (users) and operational data.

In general there are four stages in data collection: i) using already collected data, without any further modification; ii) modifying the way of collecting data previously employed in the industrial plant; iii) manually collecting further data; iv) establishing an automatic data acquisition system. Most of the core data on production are usually being gathered for other purposes (e.g. cost and production control), and some analyses should already have been done to determine which information is gathered, by whom, how, and why. Sharing this information for energy monitoring purposes may require modifications to enable a more effective energy monitoring. Its impact on other management functions should be considered - it may, or may not, be beneficial.

The energy bills are the primary source of information for the consumption data. They are the first point of reference when trying to understand what is being used, as well as how the organization is being measured and charged. In particular:

- for oil and coal the invoices report information on deliveries and consumptions. It is then necessary to take account of stocks. If stocks are not already recorded, it is important to guarantee somehow the suitability of the data. At the same time, a system for recording the stock before delivery has to be introduced.
- for gas and electricity, the information that appears on the bill depends on the tariff type.

The production information can be divided into three types:

- information on production that relates to amount as weight, volume, number of items, area (waiting time and productive hours fall into this category, as the climate measurement in heating or cooling degree days);
- information on production that does not relate to amount as temperature, density, water content, ratios of constituents (e.g. fat to solid ratios in fried food);
- ancillary information as, for example, breakdown causes, occasional notes and comments.

The first one of these is distinguishable from the other three because items of information are additive; in other terms, information for a week can be obtained by adding daily information. Information of the second type is not additive. In some cases monitoring and targeting can achieve adequate resolution only if information of this second type is utilized. Information which is not additive is difficult to summarize and this is often reflected in the way it is handled in organizations. It is more likely to be hand-written, with few checks on its accuracy, and archived without being processed (Carbon Trust, Practical guide 112).

About the environmental data, they usually can be:

- the sunlight variation for electrical energy for lighting; for these data we could refer to meteorology web sites or databases;
- heating and cooling degree day for consumption of energy for heating and cooling, respectively; we could refer to past data or data recorded by sensors in the plant.

For the last point the realization of energy audits becomes fundamental in addition to the collection of documental information and measurements with opportune campaigns, it allows the recording of useful technical data about the plant energy consumptions.

In particular the audit phase consists of inspection in the analyzed plant, interviews with the internal responsables, measurements and registrations of the machineries performances.

These data are an integration of the other documental information, in particular for analysing the production area, the use of machineries, the unsatisfied needs of maintenance. Besides, the energy audit constitutes a fundamental step for the checks of an energy management system (Carbon Trust, Good practice Guide 200), for verifying the effective results of the integrate management structure.

The most powerful energy audit instruments available in literature are the check lists and the decisional matrices (Carbon Trust, CTV 023). In particular, these instruments have been adapted to our particular procedures and integrated in this described sequence of steps.

The decisional matrices have essentially three functions:

- assessing the system energy performance;
- planning the necessary action, identifying the priorities;
- monitoring the effects of energy management systems.

Concretely they are tables characterized by three levels of detail. They allows the evaluations of distinct characteristics of a system assessing a score (from 0 to 4). (Carbon Trust, Good Practice Guide 306).

The first level (Top-Level, Energy Performance Matrix) groups the results of the other matrices and allows an overview of the organization.

TOP LEVEL						
PERFORMANCE MATRIX						
LEVEL	1	2	3	4	5	6
ENERGY MANAGEMENT						
FINANCIAL MANAGEMENT						
AWARNESS AND INFORMATION						
TECHNICAL						

Table 2. Top Level Matrix

The second level consists of four tables whose results are reported in the Top Level: Energy Management Matrix, Financial Management Matrix, Awareness and Information Matrix, Technical Matrix.

These tables allows to assess a score for the different aspects of these energy management issues. In particular the technical aspects are more deeply investigated in the third level matrices, which analyze the working and performance characteristics of the different plant end users (cooling system, heating system, HVAC system, compressed air, building characteristics, boilers, lighting system, monitoring and control system, Building Energy Management System (BEMS), etc.).

These last matrices are the most powerful instruments for the audit phase because may be used as a guide for analyzing the users performance.

In Table 3 an example matrix (for the compressed air) originally developed on the basis of the other found in the literary review is reported.

Therefore other instruments developed for helping in energy auditing are the check lists. Those divided every user in Generation, Distribution and Use and, for these sectors, make an analysis which is divided in four sections:

- evaluation: a series of questions to focalize the performance and qualities of the main parameters and assessing a score on their evaluation;
- solution – improvement: a list of possible activities to improve energy performance.
- detailed analysis: different detailed aspects which have to be analyzed and possible activities.
- technical – operational parameters: a guide for collect all the necessary technical and operational parameters of the users.

These check lists are less general than the decisional matrices but they present the advantage of characterizing in a more technical and detailed way all the most common service plant as well as the air handling, cooling system , boiler, HVAC system, etc.

In Table 4 an example of the Technical – operational parameters part is reported for the air handling system.

SCORE	III LEVEL - AIR HANDLING			
	COMPRESSORS	PIPING SYSTEM	ENERGY SAVING DEVICES	MONITORING AND MAINTENANCE
4	Multi-stage compressors, well dimensioned, with additional compressor used on demand. Electronic controls for modulating required power.	Pipe and valves well maintained; losses of 10%. An inspection every 6 months. Max difference of pressure of 0,5 bar. Ring piping system. Where possible the welding is preferable.	Sensors for range pressure individuation. Valves for interruptions compressed air require if not necessary. Avoiding of inaccurate uses.	Operational procedures for monitoring and maintenance are defined. Constant control on the humidity and temperature of the inlet air. Pressure gauges near the filters for their substitution. Periodic controls of the cooling water treatment system.
3	Multi-stage compressors, sufficiently dimensioned, with additional compressor used on demand. Electronic control for modulating required power.	Pipe and valves well maintained; losses of 20-25%. An inspection every 6 months. Max difference of pressure of 0,5 bar. Excessive pressure with loss of efficiency.	Sensors for range pressure individuation. Avoiding of inaccurate uses.	Theoretic procedures for monitoring and maintenance are defined. Constant control on the humidity and temperature of the inlet air.
2	Single-stage compressors, well dimensioned for demand peaks. Absence of electronic controls for modulating required power.	Pipe, valves and flanges with high losses. Annual inspections. High differences of pressure. Use of zone insulation valves with regulation functions.	Time control sensors. Valves for interruptions compressed air require if not necessary	Absence of preventive maintenance. Sensors for the registration of air consumptions for different floors; absence of procedures for using these information.
1	Single-stage compressors, sufficiently dimensioned. Absence of electronic controls. Loss of efficiency due to a bad regulation (compressor often works outside the limit value of pressure).	Losses of 30-40%. Inspection when required. High differences of pressure. Use of zone insulation valves.	Time control sensors.	Ad hoc maintenance; incomplete data about the air supplies. Absence of data about the air losses.
0	Single-stage compressors over dimensioned. Absence of electronic controls.	Losses of 40-50% with frequent open/close of the security valves; presence of dead legs.	Centralized control for the on/off of the system	Ad hoc maintenance; absence of data about the air supplies and the air losses.

Table 3. Third Level Matrix: air handling system

Air handling system						
Technical-operational parameters						
GENERATION		Reciprocating compressor (rotary)		Screw compressor (rotary)		
Compressor:	Roots blower compressor (rotary) single stage	Single/two stage	Multi stage	Single stage	Two stage	Centrifugal compressor
Capacity (m³/h)						
Pressure (bar)						
T outlet (°C)						
Full-load consumption (kWh)						
Partial-load consumption (kWh)						
Cooling water temperature (°C)						
DISTRIBUTION						
Pipes diameter (mm)						
Pipes length (m)						
Piping distribution scheme						
Pipes material						
USE						
Compressed air users						
Operating pressure (bar)						

Table 4. Check Lists: Technical – operational parameters of the air handling system

4.2 Energy cost & consumption data analysis

In the first step a group of information enabling energy usage to be managed more effectively within an industrial site has to be collected. Most of the needed data are available from existing meter readings, energy bills and production-related data. The aim of this step is to analyze and to give an an interpretation that allows transforming data into useful information for energy management purposes. At this step a standard spread sheet is adequate for many applications. The main analyses concern the following aspects.

Primary energy sources comparison. Once the data are collected, it is necessary to determine the amount of energy spent in the whole business, whatever is the consumed energy source.

Therefore all energy sources must be expressed in the same unit (i.e. MJ, kWh or TEP) and the proportionate use and cost of each different energy source when compared to the total energy consumption should be determined. This allows highlighting amount, cost and fluctuations throughout the year of each kind of primary energy, thus identifying an upper limit on the amount that can be saved and a benchmark to assess energy saving after improvement measures have been performed. Furthermore, these data could be compared with relevant available benchmarks for the same industrial sector. This information can also help in determining if current energy use is higher or lower than usual, or if any outside factors have an impact on how much is being used. It is possible to establish:

- if too much energy is being used;
- how current energy use compares with past figures;
- how the business compares with the industry average (where benchmarks are available);
- whether any other factors are temporarily affecting the figures; these might include cold weather, extended working hours or increased production. Understanding how these drivers are affecting energy data will give a better picture of site consumption.

In particular a “driver” is any factor that influences energy consumption, as weather is the main driver for most buildings and production is the primary driver for most industrial processes. Drivers are sometimes referred to as variables or influencing factors. There are two main types:

- activity drivers: feature of the organization activity that influences energy consumption. Examples include operating hours, produced tons, number of guests and opening hours.
- Condition drivers: where the influence is not determined by the organization activity but by prevailing conditions. Examples include weather, condition of the raw material and hours of darkness.

Specific Energy Consumption (SEC). This relevant parameter is defined as the ratio between energy consumption and an appropriate production measure (driver). It can be calculated for any fixed time period, or by batch. SECs need to be treated with care because their variability may be caused by several factors beyond energy efficiency, such as economies of scale or production problems not closely related to energy management. There are many process benchmarking schemes based on SEC and their easiness of use makes them attractive to many companies.

Current and past comparisons. This approach, suitable for buildings and industrial plants, is usually performed in a graphical form where a bar or column chart is used to compare the data from the current period with a similar previous. A tabular form of this comparison can also be used with a quantity or percentage figure for the difference. It is useful for monitoring year-on-year changes and cyclical patterns, and can also be used for daily and weekly profiles. This technique can be applied to energy data and its drivers.

Time series analysis. Also this approach is suitable for buildings and industry. Most energy managers are interested in the underlying trend of consumption or cost and trend lines are a graphical way of showing this. Typically, the trend line will be the trend of the data series over time. At its simplest, it is a line graph of the data for each period. A more refined application of the technique is to use moving annual totals or averages. This approach is useful since it reduces seasonal influence and allows highlighting other influencing factors.

Since a trend line can be produced from time-related energy data alone, it is a common technique to use at the early stages of investigating energy consumption.

Energy absorption. It is possible to estimate the energy absorption of different plant areas by measuring actual energy requirements and evaluating utilization rates.

Contour map. It offers a more pictorial use of profile information. Here, half-hourly data, typically for a month, is displayed as a multi-colored contour chart. This provides a very easy way of viewing 1 400 data points (30 days x 48 half-hours).

4.3 Energy forecasting at plant level

The core of the methodology is the definition of a consumption forecasting model that allows identifying the specific consumptions of different manufacturing lines in order to formulate the budget (step 6) and identifying the optimal energy rate in the contract renewal phase. Moreover it provides the reference for real-time energy consumption control (i.e. identifying sporadic faults or events).

The expected energy demand is calculated on the basis of mathematical models describing the influence of relevant factors (energy drivers) on the energy consumption by regression analysis (i.e. production volume is an important energy driver at the plant level). The energy consumption C , in delta time, can be defined as:

$$C(\Delta t) = E_0(\Delta t) + \alpha_1 V_1(\Delta t) + \alpha_2 V_2(\Delta t) + \dots + \alpha_m V_m(\Delta t) \quad (1)$$

where:

- E_0 is the constant portion of the consumption regardless of production volumes [kWh];
- V_i is the production volume [unit] of the i -th product;
- α_i is the consumption sensitivity coefficient with respect to the production volume [kWh/unit] of the i -th product.

Equation (1) can be calculated by a multiple regression between production volumes and consumptions. In general the production volumes of the different products are sufficient to create a consumption model but in some cases the use of other variables (such as, temperature, degree days, sunlight variations or other operational variables) is required. The $\alpha_1, \alpha_2, \dots, \alpha_n$ coefficients have to be assessed with statistical analysis on the historical data previously collected. The model has to be statistically validated.

Multiple linear regression model as statistical model does not mean only mathematical expression but also assumptions supplying the optimal estimation of coefficients α_i . These assumptions are usually connected with random error: the random error has normal distribution, it is equal to zero (on the average), supporting elements have equal variances.

Once a regression model has been constructed, it may be important to confirm the model capability of representing the actual behaviour of the industrial plant (in other terms the model capabilities of well fitting real data) and the statistical significance of the estimated parameters. Commonly used checks of goodness of fit include the R-squared, analyses of the pattern of residuals and hypothesis testing. Statistical significance can be checked by an F-test of the overall fit, followed by t-tests of individual parameters.

Moreover, the validity of the multiple regression analysis is related to the validity of the following hypotheses (Levine et al., 2005):

- *Homoscedasticity.* The variance of the dependent variable is the same for all the data. Homoscedasticity facilitates the analysis because most methods are based on the assumption of equal variance;

- *Autocorrelation*. Independence and normality of error distribution. Autocorrelation is a mathematical tool for finding repeating patterns, such as the presence of a periodic signal which has been buried under noise, or identifying the missing fundamental frequency in a signal implied by its harmonic frequencies. It is frequently used in signal processing for analysing functions or series of values, such as time domain signals. In other terms, it is the similarity between observations as a function of the time separation between them. More precisely, it is the cross-correlation of a signal with itself.
- *Multicollinearity*, which refers to a situation of collinearity of independent variables, often involving more than two independent variables, or more than one pair of collinear variables. Multicollinearity means redundancy in the set of variables. This can render ineffective the numerical methods used to solve regression equations, typically resulting in a "multicollinearity" error when regression software is used. A practical solution to this problem is to remove some variables from the model. The results are shown both as an individual R^2 value (distinct from the overall R^2 of the model) and a Variance Inflation Factor (VIF). When R^2 and VIF values are high for any of the X variables, the fit is affected by multicollinearity.

4.4 Sub-metering energy use

Metering the total energy consumption at a certain site is important, but it does not show how energy consumption is distributed across operational areas or for different applications. After the first three steps, therefore, it can be hard to understand why and where energy performance is poor and how to improve it. Installing sub-metering to measure selected areas of energy consumption could give a considerably better understanding of where energy is used and where there may be scope to make savings. Sub-metering is a viable option for primary metering where it is not possible or advisable to interfere with the existing fiscal meter. For this purpose, a sub-meter can be fitted on the customer side of the fiscal meter so as to record the total energy entering the site.

When considering a sub-metering strategy, the site have to be broken down into the different end users of energy. This might be by area (for example, floor, zone, building, tenancy or department), by system (heating, cooling, lighting or industrial process) or both. Sub-metering of specific areas also provides more accurate energy billing to tenants, if it is required. The sub-metering strategy should also identify individuals responsible for the energy consumption in specific areas and ensure that the capability to monitor the consumption which falls under their management responsibilities. Additionally, it may be worth separately metering large industrial machines.

By this way, it is possible to optimize the location of meters and minimize the total amounts, after energy absorption analysis, following the sub metering methods that are (Carbon Trust, CTV 027):

- *Direct metering* is always the preferred option, giving the most accurate data. However, it may not be cost-effective or practical to directly meter every energy end-use on a site. For a correct evaluation the cost of the meter plus the resource to run and monitor it has to be weighed against the impact the equipment has on energy use and the value of the data that direct sub-metering will yield.
- *Hours-run metering* (also known as *constant load metering*) that can be used on items of equipment that operate under a constant, known load (for example, a fan or a motor). This type of meter records the time that the equipment operates which can then be

multiplied by the known load (in kW) and the load factor to estimate the actual consumption (in kWh). Where possible, it measures the true power of the equipment, rather than relying on the value displayed on the rating plate.

- *Indirect metering*, which means combining the information from a direct meter with other physical measurements to estimate energy consumption. Its most common application is in measuring hot water energy consumption, which is usually known as a heat meter. A direct water meter, for example, is used to measure the amount of cold water going into a hot water heater. This measurement, combined with details of the cold water temperature, the hot water temperature, the heater efficiency and the specific heat of water, enables the hot water energy consumption to be calculated.
- *By difference metering* when two direct meters are used to estimate the energy consumption of a third end-use. For example, if direct meters are used to measure the total gas consumption and the catering gas consumption in an office building, the difference between the two measurements would be an evaluation of the energy consumption associated with space heating and hot water. This form of metering should not be used where either of the original meter readings is estimated, since this could lead to large errors. Also, this form of metering should not be used where a very small consumption is subtracted from a large consumption, because the accuracy margin of the large meter may exceed the consumption of the smaller meter.
- Where none of the above methods can be used, it may be possible to use estimates of small power to predict the energy consumption associated with items such as office equipment (by assessing the power rating of equipment and its usage). This method is very inaccurate and should be supported by spot checks of actual consumption wherever possible.

Generally speaking, the introduction of a monitoring system in a plant is fundamental for an effective energy management approach and it can bring the organization to the creation of a real Energy Information Systems. An EIS can be defined as a system for collecting, analyzing and reporting data related to energy performance. It may be stand-alone, part of an integrated system or a combination of several different systems. Besides meters and computers, an EIS also includes all the organizational procedures and methods that allow it to operate and it may draw on external and internal sources of data.

Energy Information Systems can be used to measure electricity, gas and water supplies. They have been successfully used by energy intensive users for many years to drive down costs and, in general, technology cost has reduced significantly over recent years. Then the approach now offers a good return on investment for less energy intensive businesses in terms of managing energy and water usage. Despite an attractive return on investment, it is not being taken up at the rate one would expect given its benefits. All the previous experience indicates that an Energy Information System, if properly used as a demand management tool, guarantees an energy consumption (and costs) reduction between 10% and 15% (Carbon Trust, Practical guide 231). In addition, effective energy and carbon management (i.e. actively managing risks and opportunities associated with climate change and carbon emissions) relies on the availability of appropriate management information. Therefore metering of energy consumption and flows within companies is an intrinsic element of continuing good energy management and carbon emission reduction. There is also a case for using an Energy Information System to reduce the amount of energy needed to guarantee meeting a given electricity demand. By knowing energy consumption profiles and the opportunities to reduce demand through better energy management, energy

suppliers may choose to use demand side management as a tool to more effectively match supply and demand and thus reduce the requirement for additional generating capacity.

For realizing an EIS a useful number of smart meters have to be installed (Carbon Trust, CTV 027). Smart meters can provide reliable and timely consumption data readily usable in an energy management program. Such meters can also eliminate problems associated with estimated bills and the potential consequences of not being able to correctly forecast and manage energy budgets. They also can be used to show the energy consumption profile of the site, which can help an energy manager identify wastage quickly. There is no universal definition for smart metering, although a smart metering system generally includes some of the following features:

- recording of half-hourly consumption;
- real-time information on energy consumption that is immediately available or via some forms of download to either or both energy suppliers and consumers;
- two-way communication between energy suppliers and the meter to facilitate services such as tariff switching;
- an internal memory to store consumption information and patterns;
- an easy to understand, prominent display unit which includes:
 - energy costs;
 - indicator of low/medium/high use;
 - comparison with historic/average consumption patterns;
 - compatibility with PCs/mobile phones;
 - export metering for micro-generators.

The essential features of smart metering are those which relate to consumption data storage, retrieval and display. Smart metering can be achieved by installing a fiscal meter which is capable of these essential tasks. Alternative metering solutions are available to bypass replacement of the fiscal meter with a smart meter. These include the use of sub-metering, for instance, a bolt-on data reader which is capable of storing and transmitting half-hourly consumption data. Other automated solutions, which are sometimes conflated with the term 'smart meters' are AMR (Automated Meter Reading) and AMM (Automated Meter Management):

- AMR: is a term that refers to systems with a one-way communication from the meter to the data collector/supplier. It can apply to electricity or gas, although gas systems require batteries to operate, which adds to the cost. AMR bolt-on solutions are available and appropriate for gas meters that have a pulse output. Remote, automatic reading is beneficial in that impractical manual reads are not necessary, and bills can always be based on actual reads, not estimates. How often a read is taken will depend on the supplier, although customers may request regular reads. However, even with AMR, the data will not be available necessarily, unless they are requested or have been initiated by the customer.
- AMM: they are systems similar to AMR arrangements, except that they allow a two-way communication between the meter and the data collector/supplier. As well as having all the benefits listed above, AMM allows for remote manipulation by the supplier. The advantage to the customer is that there is potential to display real-time tariff data, energy use, and efficiency at the meter. AMM is mostly available for electricity with some safety issues affecting AMM for gas.

The available technology for the transfer of consumption data from metering ranges from GPRS or GSM modems sending data bundles to a receiver, through low power radio

technology to ethernet/internet interfaces. When installing a metering system which makes use of remote meter reading, it may be considered which communication option is the most appropriate for each particular application. The system appropriateness depends on practical factors such as:

- meters number (including sub-meters);
- size of site(s);
- location of meters;
- power supply;
- proximity to phone line or mobile/radio network coverage.

In addition to these factors, the communication options employed will depend on the site-specific needs as well as the expertise of the metering company being employed. Therefore, it is advisable to ask the meter provider to offer the most reliable and lowest-cost solution, taking into account all of these factors.

4.5 Tariff analysis and contract renewal

The objectives of this step are to choose the less expensive solution relating to own forecasted energy load profile and to evaluate the impact of the different contractual options on the unit energy cost.

Energy bills are usually very complicated, as they consist of several components that often confuse the customer. For example energy use charges, transmission charges, demand charges, fuel adjustment charges, minimum charges and ratchet clauses are the more common components of electrical rate structures. Their knowledge and their control are the first step toward energy cost minimization. In particular below the electrical tariff is described with a lot of details because electricity is always present in industrial consumptions and it represents the most meaningful example (the electrical costs is made up of a large number of different terms). The structural changes that industries have to take into account in order to save electrical cost concern:

- *Electrical rate structure.* The electrical rate based on kWh bands overcame the flat tariff. This entails the proliferation of different proposals which are difficult to be compared, since they are not homogeneous in their formulation. Electrical energy rate could be influenced by total consumption, power furniture, voltage, time bands (tb), customer forecasting capability, and fuel price. The most common rate schedule in use is the day-time schedule. This rate structure eliminates the flat rate pricing of electricity, replacing it with a pricing schedule that varies with the time of the day, the day of the week and the season of the year. They were developed by utilities as a way to reduce the need for peaking stations. What makes this rate structure particularly effective is the variation in rates among bands. The time bands have a strong impact on the effectiveness of energy conservation measures. Under time of day rates, energy conservation efforts must address both the energy use and the demand portion of the bill. While any reduction in kWh use, regardless of when the reduction takes place, will result in lower energy costs, this rate structure increases the measure cost effectiveness that impact energy use during on peak hours while decreasing the measures cost effectiveness that impact off-peak use. This impact on peak energy use is further increased by savings in demand charges. On the other hand different proposals may not be homogeneous and comparisons could be not easy to perform for industries
- *Electrical bill components.* A careful examination of the own electrical bill is necessary to gain the best tariff option. The main components could be: kWh charges, demand

charges, electrical demand ratchet clauses, power factor charges, fuel adjustment. Indeed price contract proposals could vary as fixed price or combustible-linked variable price.

- *Electrical energy sector organization.* An industrial customer could purchase energy through contracts with wholesale suppliers or from producers on the basis of physical bilateral contracts. Therefore industries, aware of their own historical data on electricity consumption, have to be ready to face contractors. The knowledge of the market and sector organization gives the opportunity to compete on energy unit costs;
- *Power plant optimization or design* as it will be described in paragraph 4.8.

More details about tariff analysis are given in (Cesarotti et al., 2007). Briefly, the proposed methodology follows three steps. First of all it is necessary to understand the historical consumptions in the industrial process. Using the procedure defined in the paragraph 5.3 a mathematical model of the plant consumptions can be obtained. The next step is to use the consumption model to forecast the consumption for the next periods. This requires forecasts of energy drivers included in the model. Different sources could be used for this purpose. 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 or cooling: we could refer to a mean value obtained by the past years.

Besides the forecasted consumption has to be split among time bands according to the trend of consumption of the previous year. The last step is the tariff analysis: analysis of energy process allows minimization of costs in contract renewal for meeting the forecasted energy load profile. Various factors differ among offers (f_1, f_2, \dots, f_m) and have to be considered during contract renewal to determine the best one f_{opt} minimizing the cost applied to energy consumption forecast, $C(\alpha_i)$ as shown in the following equation:

$$f_{opt}(t) = \min_{j \in \{1, \dots, m\}} | f_j(t) \cdot C(\alpha_i) | \quad (2)$$

The average kWh cost (total cost divided by forecast consumption) helps point out the less expensive tariff. It is recommended a sensitivity analysis to evaluate how much the results are affected by the different hypothesis (future price of energy, future products demand, etc.). However, for the formulation of the final price it is necessary to consider other factors that affect energy tariff and are different among contractors such as formulation of price methods, costumer forecasting capability that influence the price, penalty about reactive energy, etc. Moreover, price contract proposals could vary (i.e. fixed price or variable price combustible-linked). For the final choice other qualitative factors included in the contract have to be considered, such as bonus relating to customer forecasting capability or natural gas contract with the same supplier.

4.6 Energy budgeting and control

Another important feature of energy management and of the presented methodology is planning for future energy demand. Energy budgeting is an estimate of future energy demand in terms of fuel quantity, cost and environmental impacts (pollutants) caused by the energy related activities.

This step allows formulating an accurate energy budget and monitoring the difference between budget and actual costs. This is performed by means of indicators able to

distinguish the effect of a different specific consumption from the effect of different operational conditions, e.g. different prices, volumes, etc.

First of all the energy budget has to be estimated by considering both the outputs of the energy consumption forecasting model (providing specific consumptions) and the industrial plant production plans (providing global volumes). Once energy budgeting of electrical consumptions and costs has been performed, it is possible to setup an “on-line” control.

In (Cesarotti et al., 2009) the authors propose energy budgeting and control methods that have been implemented within a set of first and second level metrics. The first level indicators allow identifying the effect of an increase of specific consumption beyond the predicted. The second level indicators allow to identify the effect of variations of price, volume, mix or load bands from the predicted.

In (Cesarotti et al., 2009), the consumption of electrical energy C (kWh) is defined with the expression in (3):

$$C = E_0 + \alpha_1 \cdot V_1 + \alpha_2 \cdot V_2 + \dots + \alpha_m \cdot V_m \quad (3)$$

where E_0 is the constant portion of the electrical consumption regardless of production volumes (kWh); V_1, V_2, \dots, V_m are the production volumes (unit); $\alpha_1, \alpha_2, \dots, \alpha_m$ are the sensitivity coefficients of the electrical consumption with respect to the production volume (kWh/unit).

The expression in (3) could be calculated by a multiple regression between production volumes and consumptions. The $\alpha_1, \alpha_2, \dots, \alpha_m$ coefficients have to be assessed with statistical analysis. The model has to be statistically validated through indicators as p-value, r^2 and analysis of variances.

In order to calculate the specific consumptions it is necessary to split the contribution of the fixed amount E_0 among the different productions. This can be done proportionally to production volumes if:

- data relating to the total production time of different products is not available;
- the different production processes are comparable in terms of electrical absorptions.

From (4) one can calculate the specific consumption SC_j (kWh/unit) of j -the manufacturing line, and therefore of j -th product, as in (4):

$$SC_j = \alpha_j + \frac{E_0}{V_{\text{tot}}} \quad (4)$$

where V_{tot} are the total production volumes (unit).

After having characterized energy consumption at a plant level, it is possible to formulate the energy budget. Therefore, we have to consider:

- energy characterization, as in the previous paragraph, that gives us the specific consumptions for each type of products as in (4);
- electrical energy prices as expected by the contract; if prices are linked to combustible (btz, brent) prices then a short-term forecasting of these indicators is requested (Cesarotti et al., 2007);
- forecasted production plans and, if the energy price varies by the TOD, also a short-term demand forecast, in order to match the tariff plan, and determine the budgeted cost.

As the tariff could vary by TOD, the budget cost of k -th month, BC_k (€), can be computed from the expected price for each tariff period of the day and the relative production volume as follows:

$$BC_k = \sum_{j=1}^m \sum_{i=1}^n p_{ijk}^p \cdot V_{ijk}^p \cdot SC_{ijk}^p = \text{sum of all elements}[(p^p V^p SC^p)_{ijk}] \quad (5)$$

where $[(p^p V^p SC^p)_{ijk}]$ is a matrix whose ij -th elements are given by the product $p_{ijk}^p \cdot V_{ijk}^p \cdot SC_{ijk}^p$; i denotes the time period of the day referring to the tariff; n is the number of time period; j denotes the product type; m is the number of product type; p^p is the planned price (€/kWh); V^p is the planned production volume (unit); SC^p is the specific consumption (kWh/unit) as calculated with (4).

After energy budgeting of electrical consumptions and costs for the industrial plant, it is possible to setup a “on-line” control. In this step we will look for variations in costs and consumptions and we will have to discern if increases in costs and consumptions have to be linked to:

- an increase of energy consumptions of a product family: in this case we have to investigate on the reason of the modification of energy consumption;
- a variation of production volumes or an increase of electrical energy prices: in this case we have to re-plan the budget.

The authors present a series of indicators for controlling the differences between BC and actual cost. These indicators have been derived from the earned value technique, usually used in project management cost/time control.

The following variables have been defined:

- Estimated Cost EC_k (€): it is the estimated energy cost of k -th month calculated considering the actual production volumes and actual tariff:

$$EC_k = \sum_{j=1}^m \sum_{i=1}^n p_{ijk}^a \cdot V_{ijk}^a \cdot SC_{ijk}^p = \text{sum of all elements}[(p^a V^a SC^p)_{ijk}] \quad (6)$$

where $[(p^a V^a SC^p)_{ijk}]$ is a matrix whose ij -th elements are given by the product $p_{ijk}^a \cdot V_{ijk}^a \cdot SC_{ijk}^p$; i denotes the time period of the day referring to the tariff; n is the number of time period; j denotes the product type; m is the number of product type; p^a is the actual price (€/kWh); V^a is the actual production volume (unit); SC^p is the specific consumption (kWh/unit) as calculated with (4);

- Actual Cost AC_k (€): it is the actual energy cost of k -th month really sustained by the company related to the actual production volumes:

$$AC_k = \sum_{j=1}^m \sum_{i=1}^n p_{ijk}^a \cdot V_{ijk}^a \cdot SC_{ijk}^a = \text{sum of all elements}[(p^a V^a SC^a)_{ijk}] \quad (7)$$

Where $[(p^a V^a SC^a)_{ijk}]$ is a matrix whose ij -th elements are given by the product $p_{ijk}^a \cdot V_{ijk}^a \cdot SC_{ijk}^a$; i denotes the time period of the day referring to the tariff; n is the number of time period; j denotes the product type; m is the number of product type; p^a is the actual price (€/kWh); V^a is the actual production volume (unit); SC^a is the specific consumption (kWh/unit).

Details about the calculation of parameters in the (5, 6, 7) are reported below.

Summarizing, the three variables are function of energy price, production volume and, specific consumption planned or actual as shown in the Table 5.

Basing the study on the previous formulation, it is possible to investigate the energy consumption behavior of the company related to the selected production volumes. So the following indicators have been formulated.

	BC	EC	AC
Electrical energy price (P)	Plan	Real	Real
Production volume (V)	Plan	Real	Real
Specific consumption (SC)	Plan	Plan	Real

Table 5. Variables

First of all we have to deal with the difference between AC_k and BC_k at k -th month. The first index is the percentage shift of the actual budget and the planned one as in (8):

$$I_{1k} = \frac{AC_k - BC_k}{BC_k}$$

(8)

In particular, the following situations could arise:

- $I_{1k} > 0$ – a positive value of index in (8) means that the company has spent more than predicted at k -th month.
- $I_{1k} = 0$ – a value of index in (8) equal to zero means that the actual cost complies with the budget at k -th month.
- $I_{1k} < 0$ – a negative value of index in (8) means that the company has spent less than predicted at k -th month.

At the same time, the difference between AC_k and BC_k could depend on a difference between the actual tariff and the planned one or by a difference between actual and planned production (for quantities or mix) or a higher specific consumption. In order to distinguish these cases, separating the contribution due to inefficiency of consumption and due to different energy drivers scheduling, we have to introduce the following indicators:

$$I_{2k} = \frac{AC_k - EC_k}{BC_k}$$

(9)

$$I_{3k} = \frac{EC_k - BC_k}{BC_k}$$

(10)

$$I_{1k} = I_{2k} + I_{3k}$$

(11)

A positive value of I_{2k} means a higher specific consumption for unit production for the same amount of production volumes. In this case it is important to analyze the energy behavior in terms of AC_k and EC_k for each production department. Then it is necessary to enquire about the cause of deviation with problem solving tools. There are many approaches to problem solving, depending on the nature of the problem and the process or system involved in the problem.

A positive value of I_{2k} highlights a variation in prices or energy drivers, assuming the consumption model obtained from regression completely reliable; the difference between the actual and scheduled values of energy drivers could depend upon:

- energy price: it could have changed during time, e.g. for electrical energy tariff if linked to combustible basket;
- production volume or mix: they could have changed during time due to for example a difference in production plan or availability of the production system;
- electrical loading in time bands: it could have changed during time due to for example a difference in production plan.

The second level indicators have been introduced in order to investigate in the difference ($EC_k - BC_k$). The difference could be linked to the following effects that have to be investigated:

- price effect: due to a variation in energy price;
- volume effect: due to a variation in production volume;
- loading effect: due to a variation in production loading;
- mix effect: due to a variation in production mix;
- interaction effect: is the differing effect of one independent variable on the dependent variable, depending on the particular level of another independent variable.

An interaction is the failure of one factor to produce the same effect at different levels of another factor. An interaction effect refers to the role of a variable in an estimated model, and its effect on the dependent variable. A variable that has an interaction effect will have a different effect on the dependent variable, depending on the level of some third variable. In our case, for example, a contemporaneous variation of different factors (volume, mix, load, price) involves a greater consumption (Montgomery, 2005).

In order to distinguish the previous effects the following nomenclature has been adopted:

- ΔP_{1k} (percent) is the percentage of the j -th production volume V (unit) planned at the i -th time band at k -th month on the total of the j -th production volume planned V (unit) at k -th month as in (12); so it represents the coefficient of electrical load of production volume planned in the different time bands:

$$\Delta P_{1ijk} = \frac{V_{ijk}^P}{\sum_{i=1}^n V_{ijk}^P} \quad (12)$$

- ΔP_{2k} (percent) is the percentage of the j -th production volume V (unit) planned at k -th month on the total production volume planned V (unit) at k -th month as in (13); so it represents the coefficient of mix of production volume planned for production:

$$\Delta P_{2ijk} = \frac{\sum_{i=1}^n V_{ijk}^P}{\sum_{j=1}^m \sum_{i=1}^n V_{ijk}^P} \quad (13)$$

where $V_{jk}^P = \sum_{i=1}^n V_{ijk}^P$ and $V_k^P = \sum_{j=1}^m \sum_{i=1}^n V_{ijk}^P$

- $\Delta \alpha_{1k}$ (percent) is the percentage of the j -th production volume V (unit) realized at the i -th time band at k -th month on the total of the j -th production volume realized V (unit) at k -th month as in (14); so it represents the coefficient of load of production realized in the different time bands:

$$\Delta \alpha_{1ijk} = \frac{V_{ijk}^\alpha}{\sum_{i=1}^n V_{ijk}^\alpha} \quad (14)$$

where $V_{jk}^\alpha = \sum_{i=1}^n V_{ijk}^\alpha$

- $\Delta \alpha_{2k}$ (percent) is the percentage of the j -th production volume V (unit) realized at k -th month on the total production volume realized V (unit) at k -th month as in (15); so it represents the coefficient of mix of production volume realized for production:

$$\Delta_{2ijk}^{\alpha} = \frac{\sum_{i=1}^n V_{ijk}^{\alpha}}{\sum_{j=1}^m \sum_{i=1}^n V_{ijk}^{\alpha}} \quad (15)$$

where $V_{jk}^{\alpha} = \sum_{i=1}^n V_{ijk}^{\alpha}$ and $V_k^{\alpha} = \sum_{j=1}^m \sum_{i=1}^n V_{ijk}^{\alpha}$

Price effect calculation.

It could contribute in the difference between estimated and planned energy cost ($EC_k - BC_k$). In order to investigate in the price effect, it is necessary to calculate the change (€) in the electrical costs at k-th month due to a variation of price. This has been calculated as in (16):

$$\text{Change for price}_k = \text{Sum of all elements}[(P^{\alpha} - P^P) \cdot V^P \cdot SC^P]_{ijk} \quad (16)$$

where $[(P^{\alpha} - P^P) \cdot V^P \cdot SC^P]_{ijk}$ is a matrix whose ij-th elements are given by the product $(P_{ijk}^{\alpha} - P_{ijk}^P) \cdot V_{ijk}^P \cdot SC_{ijk}^P$.

Therefore, the price effect (per cent) has been calculated as the ratio between the terms in (14) and the difference between ($EC_k - BC_k$) as in (17):

$$\text{price effect}_k (\text{percent}) = \frac{\text{Change for price}_k}{(EC_k - BC_k)} \quad (17)$$

Volume effect calculation. It is a candidate contributor to the difference between estimated and planned energy cost ($EC_k - BC_k$). Production volume could change over time due to, for example, a different production plan or a variation of availability of the production system.

In order to investigate in the volume effect, it is necessary to calculate the change (€) in the electrical costs at k-th month due to a variation of the production volume in terms of planned and actual one. While there percentage mix and time bands load have not been modified. This has been calculated as in (18):

$$\text{Change for volume}_k = \text{Sum of all elements} [P^P \cdot \Delta_1^P \cdot \Delta_2^P \cdot (V^{\alpha} - V^P) \cdot SC^P]_{ijk} \quad (18)$$

Where $[P^P \cdot \Delta_1^P \cdot \Delta_2^P \cdot (V^{\alpha} - V^P) \cdot SC^P]_{ijk}$ is a matrix whose ij-th elements are given by the product $P_{ijk}^P \cdot \Delta_{1ijk}^P \cdot \Delta_{2ijk}^P \cdot (V_{ijk}^{\alpha} - V_{ijk}^P) \cdot SC_{ijk}^P$.

Therefore, volume effect (per cent) has been calculated as the ratio between the term in (16) and the difference between ($EC_k - BC_k$) as in (19):

$$\text{volume effect}_k (\text{percent}) = \frac{\text{Change for volume}_k}{(EC_k - BC_k)} \quad (19)$$

Mix effect calculation. It is another potential contributor to the difference between estimated and planned energy cost ($EC_k - BC_k$). Production mix could have changed over time due to, for example, a difference in production plan or a variation of availability of the production system.

In order to investigate the mix effect, it is necessary to calculate the change (€) in the electrical costs at k-th month due to a variation of production mix. The difference in the mix coefficient, as in (13) and in (15), has been introduced to calculate the changed cost.

While the production volumes and the percentage of time band load have not been modified.

The difference in energy costs, due to a variation of production mix, has been calculated as in (20):

$$\text{Change for mix}_k = \text{Sum of all elements} [P^P \cdot \Delta_1^P \cdot (\Delta_2^a - \Delta_2^P) \cdot V^P \cdot SC^P]_{ijk} \quad (20)$$

Where $[P^P \cdot \Delta_1^P \cdot (\Delta_2^a - \Delta_2^P) \cdot V^P \cdot SC^P]_{ijk}$ is a matrix whose ij-th elements are given by the product $P_{ijk}^P \cdot \Delta_{1ijk}^P \cdot (\Delta_{2ijk}^a - \Delta_{2ijk}^P) \cdot V_{ijk}^P \cdot SC_{ijk}^P$.

Therefore, the mix effect has been calculated as the ratio between the term in (18) and the difference between $(EC_k - BC_k)$ as in (21):

$$\text{mix effect}_k(\text{percent}) = \frac{\text{Change for mix}_k}{(EC_k - BC_k)} \quad (21)$$

Loading effect calculation. Finally, also it could be potential contributor to the difference estimated and planned energy cost $(EC_k - BC_k)$. Production loading could be changed during the time due to, for example, a variation of the production plan. In order to investigate the load effect, it is necessary to calculate the change (€) in the difference in the costs at k-th month due to a variation of the production load. The difference in the loading coefficient, as in (12) and in (14), has been introduced to calculate the changed cost. Whilst production volume and percentage mix have not been modified. The difference in energy costs, due to a different loading production than planned in the budget, has been calculated as in (22):

$$\text{Change for load}_k = \text{Sum of all elements} [P^P \cdot (\Delta_1^a - \Delta_1^P) \cdot \Delta_2^P \cdot SC^P]_{ijk} \quad (22)$$

where: $[P^P \cdot (\Delta_1^a - \Delta_1^P) \cdot \Delta_2^P \cdot SC^P]_{ijk}$ is a matrix whose ij-th elements are given by the product $P_{ijk}^P \cdot \Delta_{1ijk}^P \cdot (\Delta_{1ijk}^a - \Delta_{1ijk}^P) \cdot \Delta_{2ijk}^P \cdot SC_{ijk}^P$.

Therefore, the load effect has been calculated as the ratio between the term in (20) and the difference between $(EC_k - BC_k)$ as in (23):

$$\text{load effect}_k(\text{percent}) = \frac{\text{Change for load}_k}{(EC_k - BC_k)} \quad (23)$$

Moreover, it is necessary to consider an interaction effect due to contemporaneous variation of different factors as discussed before. It is possible to calculate the contribution of interaction effect as in (24):

$$\begin{aligned} \text{contribution effect } (\%) &= 100\% - (\text{load effect } (\%) + \text{volume effect } (\%) + \\ &\quad \text{mix effect } (\%) + \text{price effect } (\%)) \end{aligned} \quad (24)$$

4.7 Energy monitoring and control

The aims of this step are:

- to distinguish between “justified” variability due to different setting of energy drivers (i.e. summer or winter for cooling) and “unjustified” variability that implies necessity to inspect equipment in order to evaluate the need of corrective action;
- to distinguish if variability is random due to common causes or it is due to assignable causes.

The authors propose a methodology for real time decision strategies based on statistical techniques of process control as CuSum (Cumulative sum of differences) control charts that differentiate variability thanks to their high sensitivity.

The point in the CuSum chart at time t is defined as:

$$\text{Cusum value } (\Delta t) = C_p(\Delta t) - C_a(\Delta t) \quad (25)$$

where:

- $C_p(\Delta t)$ is the planned consumption calculated by the forecasting consumption model;
- $C_a(\Delta t)$ is the actual consumption.

This technique is relatively simple, but very effective to identify energy savings (downward trending line) or higher rates of consumption (upward trending line). If the energy performance of a building or of an industrial process is consistent, its actual consumption will be roughly equal to the expected values (however calculated). In some periods actual consumption will exceed expected one and in others it will be less, but in the long term the positive and negative variances cancel out and their cumulative sum (‘CuSum’) will remain roughly constant. If, however, a problem occurs that causes persistent energy waste, even if the problem is minor, positive weekly variances will outweigh the negative and their cumulative sum will increase. The CuSum chart would switch from the baseline to a rising trend (Elovitz, 1995) and (Cesarotti et al., 2010).

4.8 Power plant management optimization

The main target of this step is to define the power plant component (thermal/cogenerative engines, boilers, chillers, etc.) set points satisfying the energy load of a buildings/industrial plant, pursuing a specified optimization criteria (i.e. system efficiency, costs, pollutant emissions). An optimal (accurate and appropriate) management of the energy system may lead to substantial energy (and costs) savings and/or environmental benefits without any improvement on the power plant components.

In general the equipments that can be investigated with this approach are:

- gas engines;
- gas steam boilers;
- hot water boilers;
- mechanical chillers;
- absorption chillers.

Being understood that any power plant may be treated by the proposed method. All the integrated equipments are considered as energy converters. They are characterized by inputs and outputs and are modeled as black-boxes. The outputs depend on the component load. It is worth of noting that, although the output could be more than one, as in the case of

a gas engine cogenerator (electricity and hot water for example), each equipment is usually defined by only one input (fuel or electric energy).

Conservation equations are considered to solve each subsystem with a quasi-steady approach (i.e. the variables are considered constant between two time-steps) (Weron, 2008), (Farla & Blok, 2000).

The input variables involved in the mathematical representation are subdivided into two main classes, as proposed in (Barbiroli, 1996): controllable and non-controllable variables. The non-controllable inputs are those related to the energy requirements (i.e. dependent on plant production plan or the building operation), as, at each time-step, the power plant has to supply the “non-controllable” energy demand.

The energetic non-controllable inputs are the cooling demand (\dot{Q}_{CD}), the low temperature heat demand (\dot{Q}_{HWD}), the high temperature heat demand (steam) (\dot{Q}_{SD}) and the electricity demand (P_{EID}). The economic non-controllable inputs are the fuel cost (c_f) and the electricity cost. Considering that electricity can be purchased by or sold to the public network, as the power plant electricity output may be higher or lower than the electric demand, the energy costs in sale (S_{EI}) and in purchase (c_{EI}) are considered. The controllable inputs are the power plant component set points varying from 0 (representing switching off) to 1 (representing maximum load). The total cost (TC), the electricity cost and consumption (ElC, P_{ElBal}), the fuel cost and consumption (FC, \dot{m}_{Tf}) are the model outputs. The optimization procedure is performed on one or a combination of the above outputs.

Simulations are performed pursuing the goal of optimizing the equipment operation, in order to satisfy specified criterion. Currently, three “optimization criteria” have been implemented:

1. minimum cost of operation;
2. minimum fuel consumption;
3. minimum pollutant emissions (CO, NO_x, SO_x, soot, CO₂).

For the last strategy different weights of the different pollutant emissions may be applied. In the present work, we have assumed that they are proportionally weighted with the Italian legislation maximum limits, as reported below. A back-tracking algorithm is used for the optimal solution identification. The numerical representation of every subsystem is summarized in Table 1. Each equation is representative of the energy transformations taking place into the correspondent equipment between input and output. Efficiency forming equations are set point dependent, according to the manufacturer specifications. The efficiency (η) of each equipment (x) is represented by a k-th order polynomial function as it follows:

$$\eta = \sum E^k \cdot SP_x \quad (26)$$

where E is the primary input energy and SP_x the equipment set point at every time-step.

As an example, a cogenerator can be represented as a black-box where fuel is converted, through an efficiency function like (26), in electricity, thermal energy (both low and high temperature) and cooling energy, as shown in Figure 2. The energy model can be divided into two main submodels: the electricity balance and the thermal balance.

5. Case study

The proposed methodology has been applied to an industrial plant that does not adopt any particular energy management strategy. The company is involved in the production of household ovens and cooking planes for kitchens.

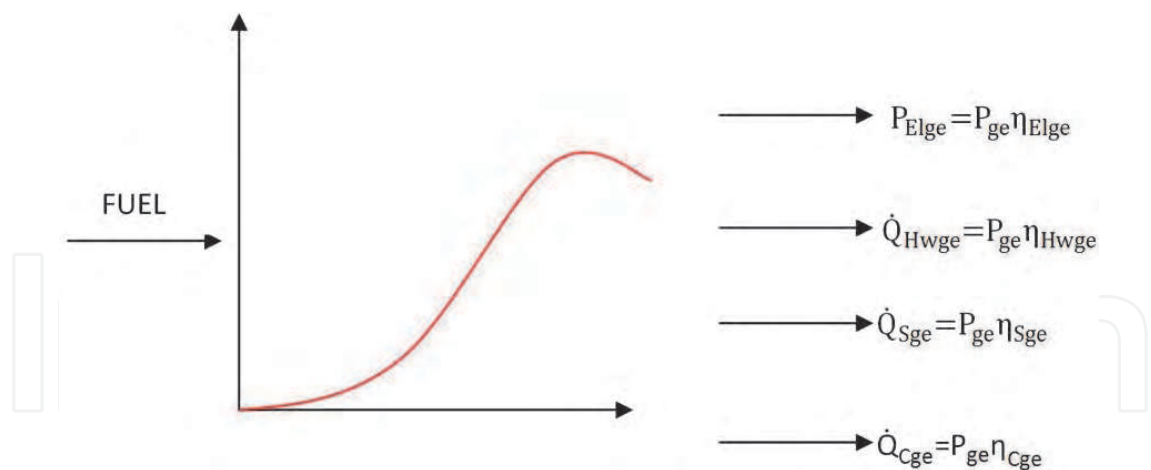


Fig. 2. Representative model of a trigenerator

Equipment	Electrical power	Chemical power	Hot water power	Steam power	Cold power
Gas engine	$P_{Elge} = P_{ge} \eta_{Elge}$	$P_{ge} = \dot{m}_{fge} H_i S P_{ge}$	$\dot{Q}_{Hwge} = P_{ge} \eta_{Hwge}$	$\dot{Q}_{Sge} = P_{ge} \eta_{Sge}$	$\dot{Q}_{Cge} = P_{ge} \eta_{Cge}$
Mechanical chiller					$\dot{Q}_{Cmc} = P_{mc} COP_{mc} S$
Absorption chiller					$\dot{Q}_{Cac} = \dot{Q}_{Hwac} COP_{ac}$
Hot water boiler			$\dot{Q}_{Hwb} = \dot{m}_{fHwb} H_i \eta_{Hv}$		
Steam boiler			$\dot{Q}_{Sb} = \dot{m}_{fSb} H_i \eta_{Sb}$		

Table 6. Subsystem characterization

The production volume has been grouped in 5 product families representing the entire production: household oven n°1 (HO1), household oven n°2 (HO2), household oven n°3 (HO3), cooking plane n°4 (CP4) and, cooking plane n°5 (CP5). The plant produced several different products classified by shape and size, and identified by a specific tag.

The production process is made up of the following working cycle: sheet metal forming by means hydraulic presses; welding and folding; glazing; quality control; sticking; assembling; final quality control.



Fig. 3. ASME process description

The aim of the project is reducing specific energy costs through the application of the methodology previously illustrated.

The steps 1 and 2 of the proposed methodology have allowed identifying overall plant energy costs and consumptions due to electrical energy and gas, and to evaluate their distribution among the different production areas. Electrical energy consumption was 10 GWh/year which took to a cost of about 1.1 million €. Regarding the gas, a consumption of about 3 MSm³/year took to a cost of just little more of 1 million €. The amount of global cost was about 2 100 000 €/year with an incident on final product cost of about 3 €/u.

The primary energy consumption (TEP) distribution is 48% electricity (1MWh = 0.23 TEP) and 52% natural gas (1000 Sm³= 0.82 TEP), while energy cost is distributed 52% for electricity and 48% for natural gas due to the higher unit price (€/TEP) of electricity as shown in Figure 4.

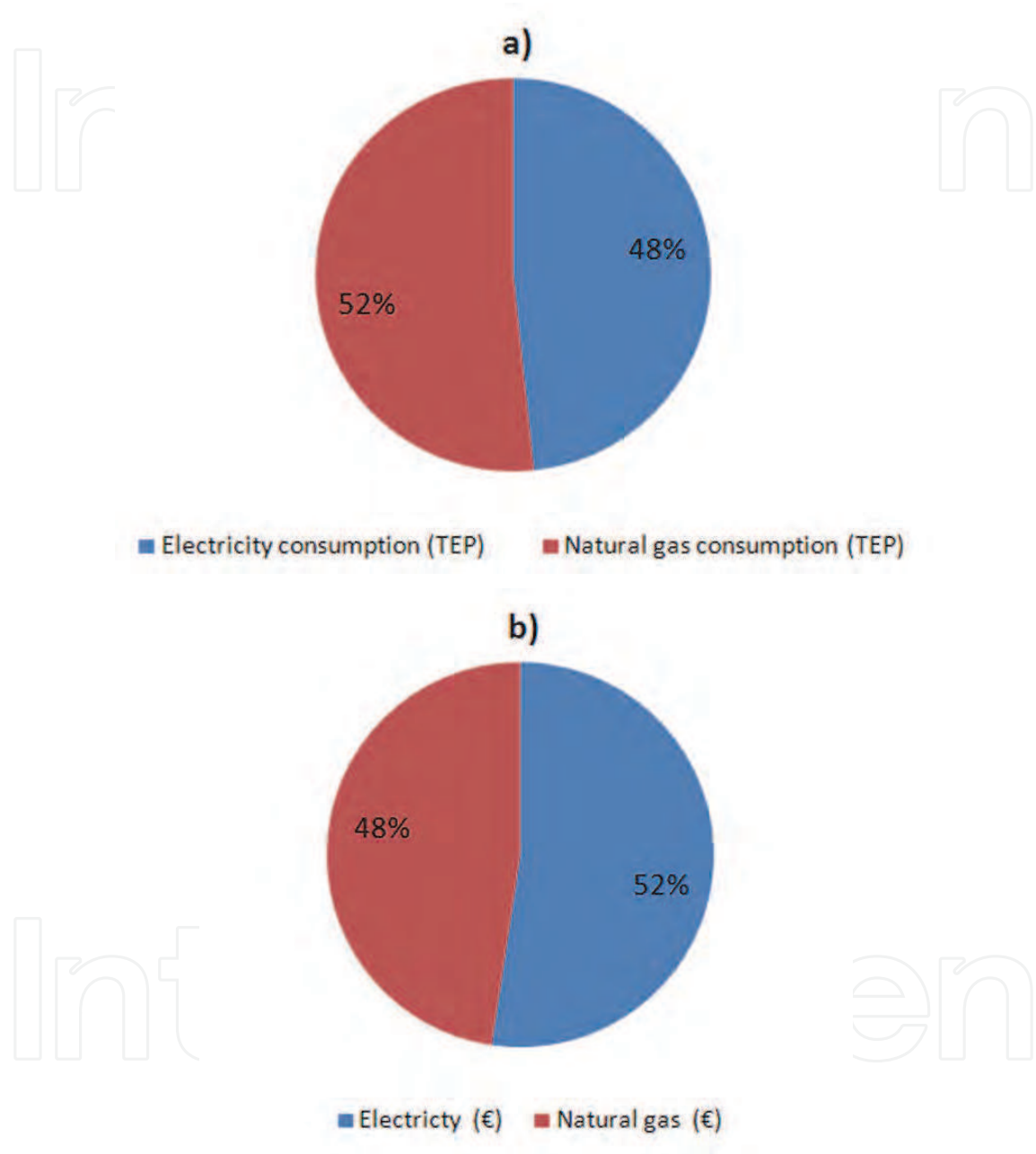


Fig. 4. Distribution of energy consumption (a) and cost (b)

The industrial plant features only one electrical meter on the main electrical transformer booth and only one gas meter on the main panel. Therefore, in order to identify the energy consumption distribution, an assessment has been carried out and a measure campaign of absorbed active electrical power for zone has been performed. As a result the compressors, hydraulic presses and welding machines represented 60% of the whole electrical consumption as shown in Fig. 5a.

A measure campaign of consumed natural gas in each zone of the industrial plant revealed that 72% of the whole gas consumption is consumed for the glazing area (41% for furnace 1 and 31% for furnace 2) and, 28% in the boilers employed for heating and hot water production for grease removal as shown in Fig. 5b.

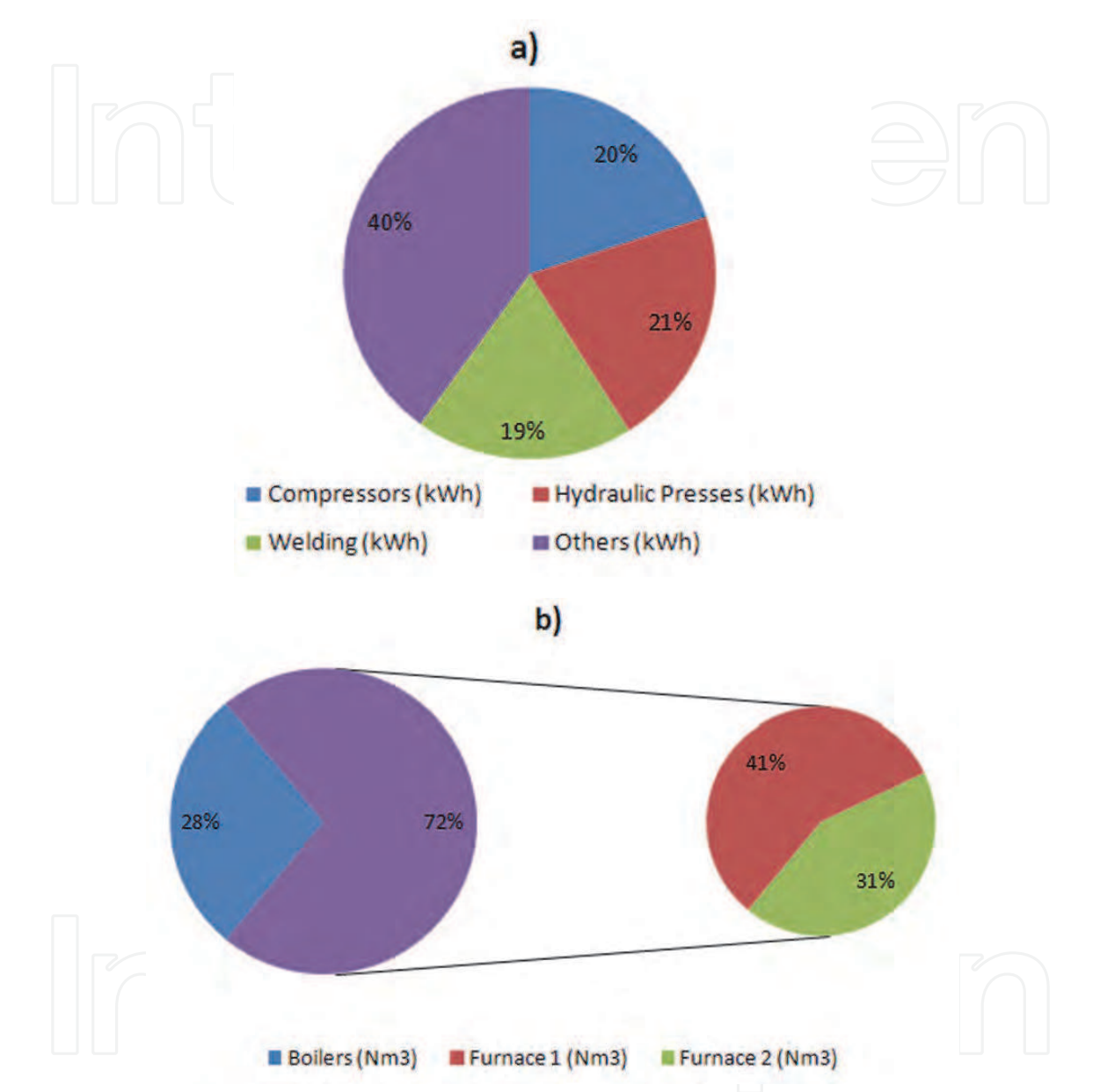


Fig. 5. Distribution of electrical consumption (a) and natural gas (b)

The hourly data recorded by the central electrical meter allow the characterization of the consumption in terms of main load profile of the entire plant and the realization of useful graphical representations as well as the contour map. Two examples of these further analysis are reported in Figure 6 and Figure 7.

A detailed analysis of the energy bills for the previous thirty-six months revealed a mean electricity cost of 0.11 €/kWh, which is sufficiently high to highlight a saving opportunity by changing the electrical contract. On the contrary, the gas costs did not appeal for saving.

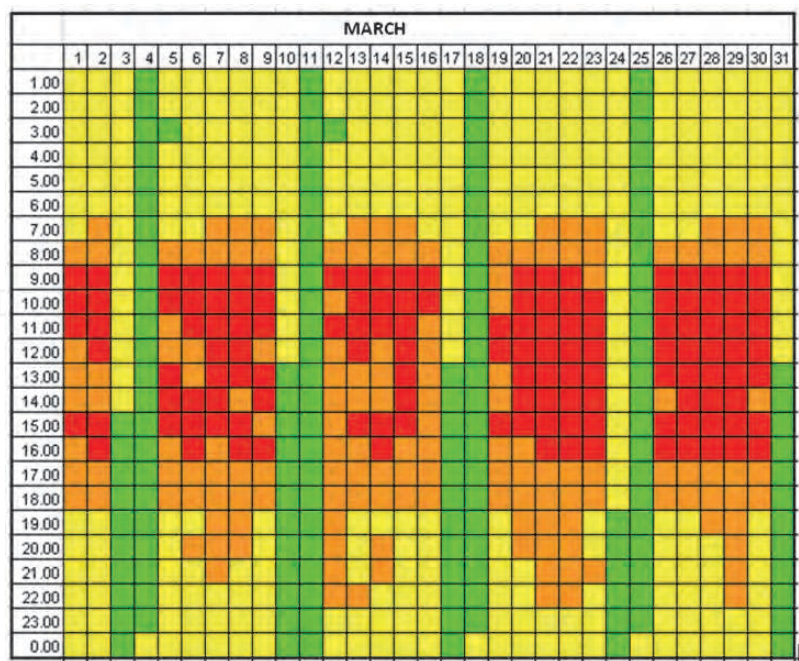


Fig. 6. Contour map: electrical consumptions in March

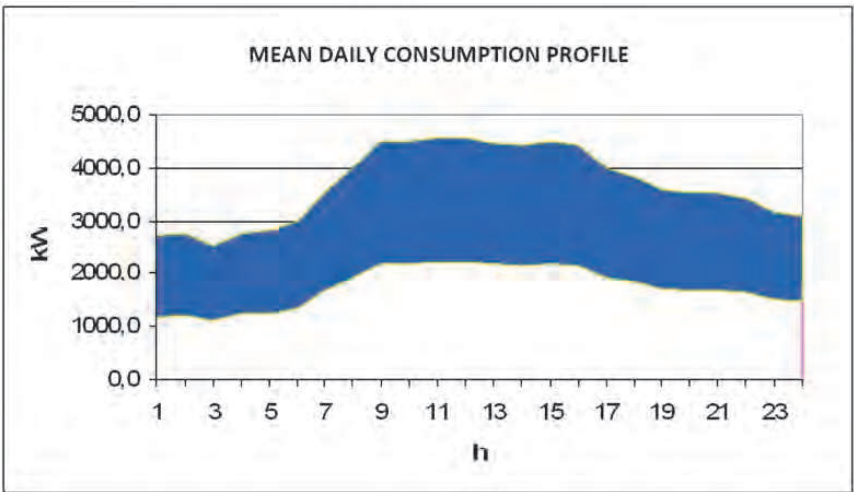


Fig. 7. Mean load profile for a weekday

Therefore after this preliminary step, following the methodology step 3, the energy drivers for the characterization of electrical consumption of the main and unique electrical meter and gas meter have been identified. As already remarked, the production volume has been grouped into 5 product families, assumed to be the energy drivers for electricity consumption. Data related to the electrical consumption of the years 2005, 2006, 2007 with monthly time resolution and the production volume per each product family have been considered and the statistical software MINITAB has been used . The output of the regression model is:

$$C\left(\frac{\text{kWh}}{\text{month}}\right)=460\,602\left(\frac{\text{kWh}}{\text{month}}\right)+4.21\left(\frac{\text{kWh}}{\text{unit}}\right)\cdot V1\left(\frac{\text{u}}{\text{month}}\right)+1.55\left(\frac{\text{kWh}}{\text{unit}}\right)\cdot V2\left(\frac{\text{u}}{\text{month}}\right)+4.42\left(\frac{\text{kWh}}{\text{unit}}\right)\cdot V3\left(\frac{\text{u}}{\text{month}}\right)+5.51\left(\frac{\text{kWh}}{\text{unit}}\right)\cdot V4\left(\frac{\text{u}}{\text{month}}\right)+10.5\left(\frac{\text{kWh}}{\text{unit}}\right)\cdot V5\left(\frac{\text{u}}{\text{month}}\right)\tag{27}$$

Predictor	Coef	SE Coef	T	P
Constant	460602	34472	13,36	0,000
H01	4,212	1,018	4,14	0,000
H02	1,547	1,044	1,48	0,149
H03	4,423	1,067	4,14	0,000
CP4	5,5098	0,9181	6,00	0,000
CP5	10,527	1,147	9,18	0,000

S = 3304,60 R-Sq = 87,6% R-Sq(adj) = 85,6%

Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	5	2323097489	464619498	42,55	0,000
Residual Error	30	327611160	10920372		
Total	35	2650708649			

Fig. 8. Statistical parameter for model validation

The statistical validation of the regression model, shown in Figure 8, is characterized by a squared regression coefficient, R^2 , of about 87.6%, thus denoting a strong correlation. The p-values in the table show the reliability of the regression coefficients and the analysis of variance shows a controlled residual error. The model is consistent for the analysis: after the analysis of statistical measures and their positive results we can discuss the characterization model and in particular we pointed out that 460 602 kWh/month was a consumption independent of production volumes.

As the energy consumption model is now available, the forecast of energy consumption in the year 2008 can be performed on the basis of the predicted production volume of each product family for the same year provided by the company.

By this way it is possible to work with a reliable forecasting consumption for the contract renewal, following the methodology in the step 5.

The original electric energy contract features three time bands, F1, F2 and F3, with unit costs 0.15 €/kWh, 0.09 €/kWh and 0.06 €/kWh, respectively. The consumptions distribution per band was 41% in F1, 53% in F2, 6% in F3.

The methodology application to this plant allowed the contract renewal, enabling the choice of the best tariff among the Italian free energy market. Ten different tariff proposals (both fixed and combustible basket linked) considering 2 (peak – off-peak) and 3 (F1, F2, F3) bands have been considered and compared. The tariff proposals and the resulting energy costs are summarized in Table 7.

The consumption forecast based on the production volumes yields an overall consumption of about 15 GWh/year subdivided into the rate bands as follows:

- 52% in F1, 35% in F2, 13% in F3;
- 81% peak, 19% off-peak.

The predicted consumption per band allows calculating the unit energy cost, in order to identify the optimal electrical tariff. This is the only way to have a clear vision of the electricity unitary price and a homogeneous basis to compose the total cost. Following this approach, the best tariff is the bidder 4 (see Table 7), that is a three-time bands characterized by the following unitary prices (F1 = 0.13 €/kWh, F2 = 0.1 €/kWh, F3 = 0.05 €/kWh).

Fixed	Combustible basket linked	F1, F2, F3	P , OP	# of bidder	Average cost with regression model (€/kWh)	Average cost without regression model (€/kWh)
X		X		Bidder 1	0.1173	0.1128
X			X	Bidder 2	0.1123	0.1099
	X		X	Bidder 3	0.1157	0.1123
X		X		Bidder 4	0.1091	0.1093
	X	X		Bidder 5	0.1143	0.1109
	X	X		Bidder 6	0.1122	0.1098
X		X		Bidder 7	0.1201	0.1189
	X	X		Bidder 8	0.1134	0.1109
X		X		Bidder 9	0.1121	0.1087
	X		X	Bidder 10	0.1267	0.1178

Table 7. Characteristic and calculation of optimal tariff

After contract renewal, the company aimed to understand the evolution of energy cost and consumption and defined a reliable budget, following the methodology in the step 6. Therefore, after energy consumption characterization and prediction, the budget has been calculated considering the following information:

- the forecast of production volume for 2008 that has been provided by the company;
- the electrical energy tariff has been fixed equal to (F1 = 0.13 €/kWh, F2 = 0.1 €/kWh, F3 = 0.05 €/kWh);
- the production has been scheduled 52% in F1, 35% in F2, 13% in F3.

The plant has to be operated mostly during peak hours due to the constraint stated by union agreement and to the convenience of factory workers hourly cost during peak time. This component had more influence on the final product cost than the energy cost. In particular the different products were made in different lines operating simultaneously during the production time. So there was no difference in terms of absorption. The 2008 planned budget was 1 636 500. €. It has been evaluated considering a reliable forecasting of consumption, the best tariff renewal and the optimization of the energy machines management.

The effectiveness of the proposed approach is highlighted by the real energy consumption of the industrial plant in 2008.

The optimal tariff led to a mean energy cost of 0.1091 €/kWh, against 0.1173 €/kWh of the original one, thus yielding a whole saving of about 120 000 €. It is worth of underlying that a tariff comparison on a fair basis could be done thanks to the forecasting model (i.e. integrated approach), as the same comparison based on the simple historical data analysis would have led to wrong choices. Only considering the historical data, in fact, the “best” tariff would have been the bidder 9, a 3 time bands with the following unitary costs F1 = 0.14 €/kWh, F2 = 0.09 €/kWh, F3 = 0.06 €/kWh. The application of this tariff would have given an actual energy cost of 11.21 cent€/kWh, about 7% higher than that given by the bidder 4. Choosing bidder 9 in place of bidder 4 would have led to a loss of 45 000 € in 2008. The industrial plant behavior, in fact, may significantly change from year to year, especially

in the case of multi-product plants, thus leading to energy drivers modifications. This means that simply employing historical energy consumption data would not take into account these changes, thus leading to wrong conclusions. It is obvious that the more the industrial plant production is variable, the more the integrated approach is effective.

In relation to the energy budgeting, the planned budget error was only of 1% relating to the actual data for energy expense for the 2008. Formulating the energy budget only considering the historical data and the old tariff not renew, we would have obtained a budget of 1 173 000 € with an error of 10% respect the actual energy expense for the 2008 even under hypothesis to increase the forecasting of 30% linked to an increase of the production volume. This error would have entailed not correct allocation of the budget cost with a consequence on the final cost balance of the year.

For the 2008, in order to monitor the energy intensive areas of the plant, the company decided to install both electrical and gas meters in the plant. A measure campaign has been carried out as described above in paragraph 5.4. Accordingly to the previous consumption splitting up, following the methodology step 4, the planned distribution of electrical and gas meters are shown in Figure 9. An energy information system has been implemented in order to analyze energy data and to control real time the consumption following the methodology step 7.

Measuring system installation allowed to implement a real time control of consumption both on compressors and hydraulic presses. The authors show an application on the hydraulic press as an example. First of all the statistical model of electrical consumption has been defined considering as energy driver the strokes of hydraulic press at quarter hour (strokes/15 min).

A linear regression model has been built on the hydraulic press meter, with a quarter hour time resolution, as follows:

$$C(\text{kWh}) = 6.5 (\text{kWh}) + 0.5 \left(\frac{\text{kWh}}{\text{strokes}} \right) S(\text{strokes}) \quad (28)$$

$$R^2 = 98\% \quad (29)$$

Then a CuSum control chart has been implemented to monitor deviation to normal consumption. The cumulative sum of difference between actual and predicted value of consumption was automatically plotted on the chart as in Figure 10. The CuSum can be used to monitor consumption process variability and it allowed to distinguish between random variability and variability due to different utilization conditions. Such a situation occurred as energy drivers were included in the predicting model. Hence a deviation in normal consumption is pointed out when the points in the chart exceed a previously defined statistical limit. The CuSum were implemented and automatically upgraded with data registered by electrical meters and sensors.

Figure 10 shows part of the CuSum evolution. In the first part the CuSum has a flat trend and is below the first limit value, thus highlighting a good agreement with the prediction of the consumption model.

Then a significant and progressive increase is observed, due to an unexpected energy consumption rise, which is to say an extra energy consumption not related to the chosen energy drivers.

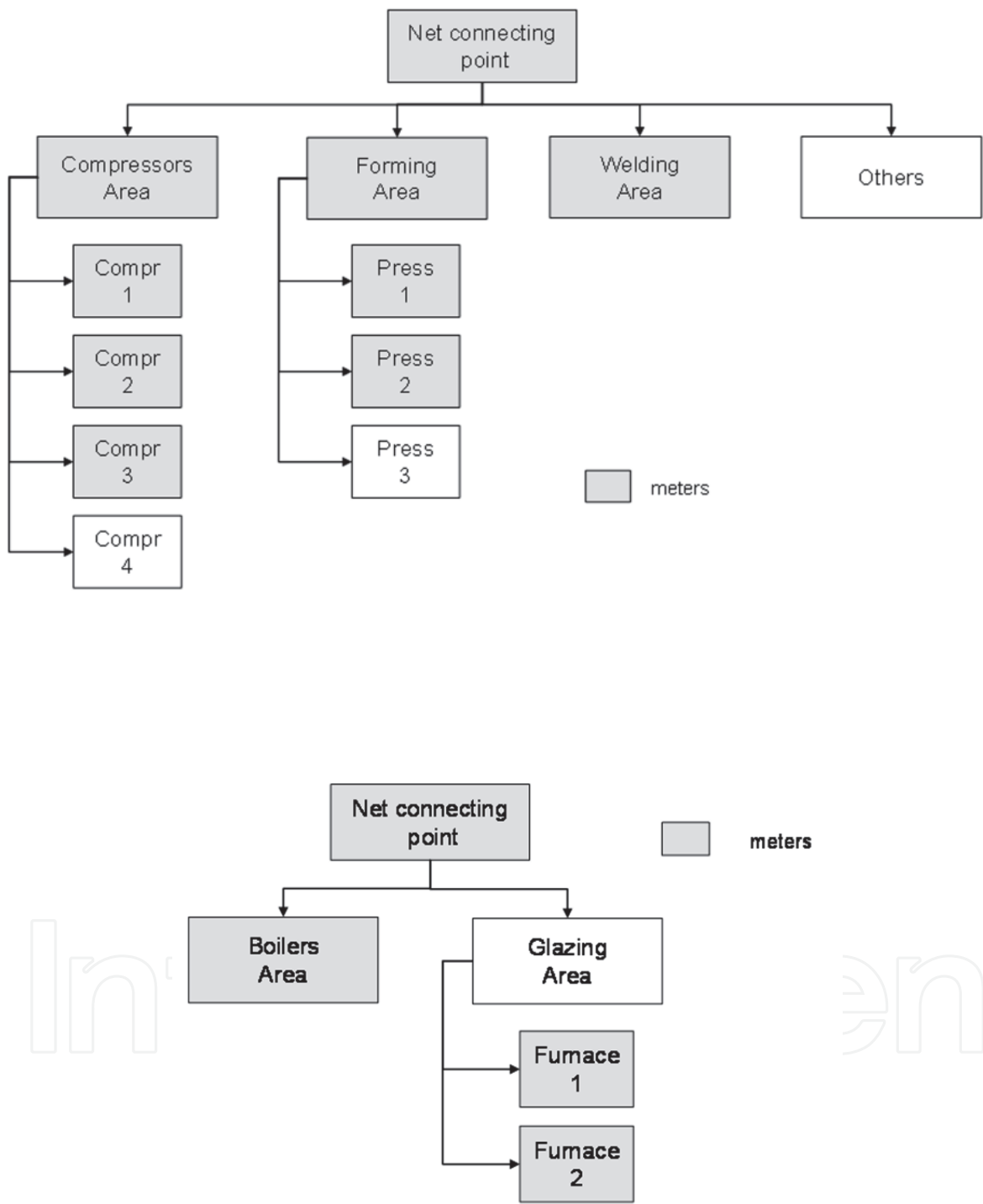


Fig. 9. Distribution of electrical and gas meters



Fig. 10. CuSum of the hydraulic press energy consumption

Due to the modality of CuSum construction a meaningful change in the slope of the curve highlights the presence of energy consumption anomalies. A warning or an alarm for the operator could be set when the CuSum reaches an upper or a lower limit. As proposed in (Cesarotti et al., 2010), the first (warning) limit values are the $\pm 3\sigma$ of initial population, the second (alarm) limit values are set evaluating the particular sensitiveness of the monitored users.

Using these limit values, an alert has been given (in October 2008) to point out that energy was being wasted; the emerged problems were essentially linked to bad maintenance procedures and an excessive heating of hydraulic oil.

The improvement in these two topics bring a great change in the press performance, as it's reported in Figure 11; in Table 8 an estimate of the reached saving is also described.

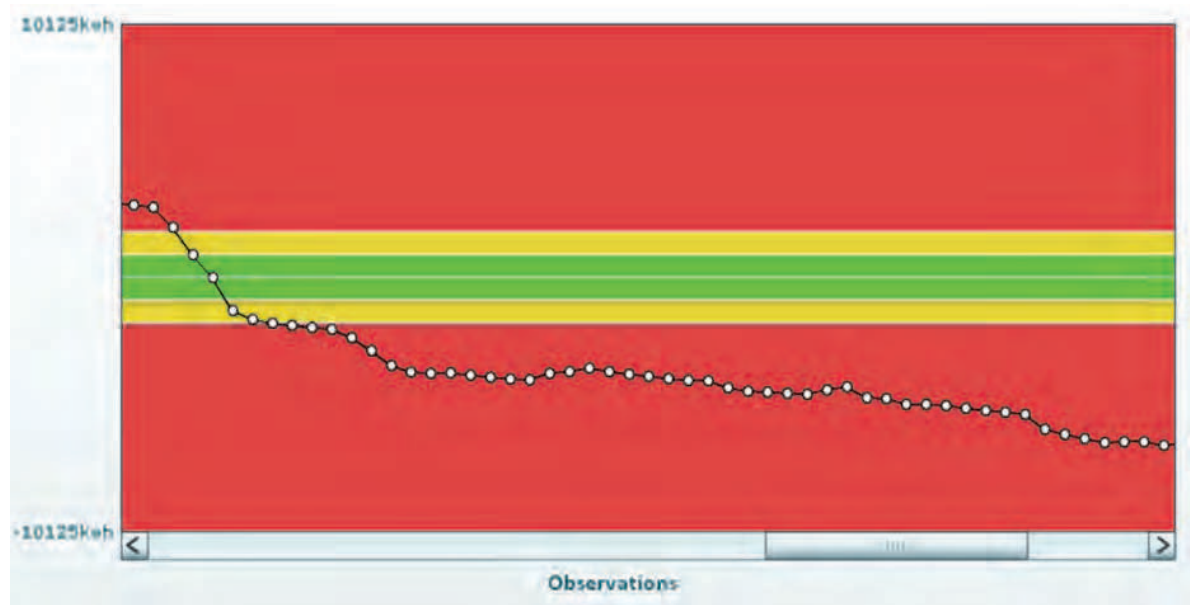


Fig. 11. CuSum of the hydraulic press energy consumption after maintenance

	kWh/year	€/year
2008 assessment	827 030	€ 104 206
2009 assessment	734 518	€ 92 549
Difference	92 513	€ 11 657
% Saving	11%	

Table 8. Savings evaluation

The implemented method allowed a control that it was not a simple monitoring of the actual consumption of the hydraulic press but it was a control based on the comparison with the planned consumption. Indeed the planned consumption was referred to the strokes/min that drive the consumption of the press and statistically reliable. Finally the accurate setting out of the sub-meters in the plant allowed to circumscribe the analysis of deviation.

The use of control chart allowed to find out different behaviors depending on the monitored system as:

- anomalous use of the system (systems or components left on during no operating time);
- physical limit of the system users (i.e. compressor with constant power absorption that does not adapt to variable demand of air of the final user);
- anomalous system operating conditions due to need of maintenance (i.e. inefficient thermal transfers due to calcareous coat, anomalous press consumption due to lack of lubrication, etc.).

Finally the company has been interested, for the strategic future plans, to simulate a power plant to produce energy.

The simulated power plant consisted of a cogenerative gas engine producing part of the plant electrical and thermal energy for hot water and steam. The engine was used to be on during daily time (i.e. 8 a.m. – 18 p.m.) and the other equipments were used to satisfy the company energy loads. No particular strategy was applied to optimize the use of the cogenerative engine. The power system behavior has been translated into a mathematical model, as the one described in (Andreassi et al., 2009), which emulates the energy/mass balances existing between the power plant and the building. The model allows matching the industrial plant energy demands (electricity, hot water, cold, etc.) through an analysis of the system performance characteristics, taking into account the main subsystems integration issues, their operation requirements and their economic viability. All the integrated equipments are considered as energy converters. They are characterized by inputs and outputs and are modeled as black-boxes. Conservation equations are considered to solve each subsystem with a quasi-steady approach (i.e. the variables are considered constant between two time-steps). Simulations are performed pursuing the goal of determining conversion efficiency and energy cost with optimised equipment operation, in order to satisfy specified criterion. In this case the minimum energy cost have been chosen as the optimization criterion (other could be minimum fuel consumption or minimum pollutant emissions). It is worth to underline that this kind of analysis takes into account the possibility of selling excess energy and the different cost of the same fuel as a function of its utilization (i.e. different taxes are applied if the same fuel is used for heat or electricity production).

Beyond the saving obtained through the power plant management optimization, it is important to highlight its strong correlation with the other methodology steps, and in

particular the forecasting model and the tariff analysis. The economic and consumption advantages descending from a comprehensive application of the proposed methodology is shown in Table 9. As expected an increasing modules integration maximized the cost saving that was about 220 000 €/year.

Electrical power (cosφ=1)	kW _e	1 063
Thermal power	kW _e	642
Electrical energy	kWh _e	2 750 194
Thermal energy for hot water about 90°C	kWh _t	1 694 880
Thermal energy for steam	kWh _t	1 502 160
A) Electrical energy costs	€	336 649
B) Hot water energy costs	€	61 721
C) Steam costs	€	54 703
D) Natural gas costs	€	233 601
Saving	€	219 472

Table 9. Economic plan of the investment

6. Conclusions

A methodology pursuing the energy management improvements is presented. Each step constituting the proposed process is illustrated, underlying the main operational aspects and the distinctive characteristics. The relations between the methodology steps and some significant results emphasizing the main aspects are reported.

In particular the importance of establishing a complete monitoring system is underlined and the methodological instruments for controlling the energy performance of an organization are described. The proposed methodology helps the organizations to establish an effective energy management system which can:

- develop and understand of how and where energy is used in the facility;
- develop and implement a measurement method to provide feedback that will measure performance;
- benchmark energy use against other comparable facilities to determine how energy efficient an organization is;
- identify and survey the energy using equipment;
- identify energy conservation options and prioritize their implementation into an energy management plan;
- review the progress on an ongoing basis to determine the program’s effectiveness.

The application of this methodology to a case study highlights the effective convenience of this approach. The data collection and analysis allowed the characterization of the energy profile of the organization, in terms of consumption, costs and future trends. Useful instruments (as the contour map and the mean profiles) have been applied. A forecasting model has been calculated for studying the future consumption and make possible correct budget consideration: in particular a 10% saving has been obtained with a contract renewal

and the final error in budget allocation is about 1%. The case study also demonstrated the effectiveness of an energy monitoring system in order to identify in short time inefficiencies of the energy users; it allows a rapid alarm and the possibility to plan the necessary actions to reduce energy costs. In this case the organization cost reduction was 11%, eliminating inefficiencies in the hydraulic press.

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