Energy budget control in manufacturing systems with on-site energy generation: an advanced methodology for analyzing specific cost variations

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Abstract: In light of the growing competitiveness in global economy and the raising energy prices, energy budget management is an increasingly critical aspect for manufacturing companies. However, the analysis of the energy budget variation over time can be challenging due to numerous parameters affecting specific energy cost and energy consumption. The present study falls within the context of various works in literature concerning energy budget control and has the purpose of focusing the analysis on complex manufacturing systems including an on-site energy generation plant. In this case, the contributions of energy produced on-site, purchased and sold will contribute to the definition of the specific energy cost, which will be in turn influenced by several factors such as market prices of the resources (electricity, fossil fuel), specific characteristics of consumption (quantity and load synchronization), efficiency of the production system. In order to implement a comprehensive control of the energy budget, the difference between the predicted values and the real ones (budget variations) should be broken down into various components. This work proposes a methodology to decompose budget variations, defining a series of indicators at different levels associated to the single components influencing the variation itself, thus enabling the identification of the specific causes. This methodology has been developed in response to the demand of a specific company but can also be applied to others with similar configurations, given the interest recently aroused in this topic. Its application in an industrial context is then presented. The result of this work is the definition of a system of indicators allowing the identification of the different causes of the budget variance. The clear attribution of such deviations to different responsibility centers is enabled by the identification of a set of parameters to keep under control, hence supporting the company in the definition of timely countermeasures.

Keywords: Energy Performance Indicators, Energy budget, Budgetary control

1. Introduction

Energy management is a topic of increasing importance in the industrial context. A comprehensive and conscious application of the principles of energy management has a strategic value besides the diffusion of energy efficiency. It is a strategic asset in a highly competitive global marketplace, in the perspective of increasing energy prices. (Sa et al., 2017). A proper energy management is a tool to gain competitive advantage and flexibility, reducing the cost of production or services while meeting customer service needs for quality and delivery times. (Introna et al., 2014; Doty and Turner 2007). In fact, as stated by Piper (1999) "Economic considerations have always been the primary driving force behind energy management". As stated by Carbon Trust (2011) "Energy management is the systematic use of management and technology to improve the energy performance of an organisation. To be fully effective it needs to be integrated, proactive and incorporate energy procurement, energy efficiency and renewable energy." A confirmation of the growing interest in this theme is the publication of the ISO 50000 series of international standard concerning Energy Management and the increasing number of enterprises that undertake the process for certification every year (the Energy Management Systems certified in 2013 and in 2014 have been respectively 2590 and 1939, whereas in 2015 the number of certifications acquired has been 5220) (ISO).

One of the main tasks for management is budgeting (Morvay et al., 2008). According to Capehart et al. (2003) "a good energy accounting system is implemented in three phases: (1) design and installation of accurate metering, (2) development of an energy budget, and (3) publication of regular performance reports including variances". Energy budgeting is a key aspect in monitoring the energy performance of an organization. Only by controlling the difference between prediction and actual performance of the plant and identifying the causes for this occurrence, it is possible to take countermeasures and implement a continuous improvement.

On the other hand, as stated by the European Commission (2017) the electricity market is facing a change, with the development of a more flexible and decentralized electricity production and new technological opportunities for consumers to actively participate in the electricity market and so reduce their bills through demand response, self-consumption and energy storage.

1.1 Diffusion of on-site energy generation systems

The diffusion of on-site energy generation systems is continually increasing and the number of industrial companies that decide to invest in systems that allow them to provide their own energy demand independently is becoming larger every year (Rezaee Jordehi, 2016; Keller et al., 2016). Many companies, in fact, are choosing to switch over to on-site generation systems, finding it a more profitable alternative then obtaining the power they require from the public grid.

The technologies commonly used for on-site generation can be distinguished between non-renewable and renewable energy based ones and are the following (Prakash and Khatod, 2016): integrated gasification combined gas turbine, micro turbine, internal combustion (IC) engine, solar thermal and solar photo-voltaic, small and micro hydro, wind turbine, bio-mass energy and geothermal energy.

The benefits deriving from the implementation of an on-site generation system are not only economic, but also technical and environmental. In general, the technical benefits concern the improvement of the voltage profile and power quality, the reduction of the losses of the line and the stress on transmission systems and the enhancement of the overall reliability and security of the power system (Rezaee Jordehi, 2016; Paliwal et al., 2014). Moreover, the emission of pollutants is reduced and the diversification of energy sources is increased, halting fuel scarcity (Prakash and Khatod, 2016; Paliwal et al., 2014).

1.2 Background

Implementing a comprehensive control system of the energy budget involves the evaluation and analysis of the difference between the predicted values and the real ones. In order to execute a budgetary control, top management should identify if and in what measure the actual performance differs from the planned one, analyze the reasons behind the occurrence and allocate the responsibility to different cost/responsibility centers (Donelly and Foley, 2003).

The development of indicators is a crucial tool for policy-making and operative control (Benedetti et al., 2016). As stated by the Institute of Energy Economics in Japan (2000) "Indicators can be denominated in either physical units, where energy is directly related to the physical quantity of output, or alternatively in economic terms, where energy consumption is linked to the monetary value of production".

Many studies have been conducted in order to create different tools to control and improve the energy performance. A variety of EnPIs (Energy Performance indicators) has been developed using different approaches, as also stated by the international standard ISO 50006:2014.

The tailoring of appropriate performance indicators is a critical issue also been addressed in regards of production performance and sustainability (Fantini et al., 2015; May et al., 2015; Nakajima, 1988; Narula and Reddy, 2015).

Multiple measurement and indicators are available in literature to assess the energy efficiency performance in industrial context (Tanaka, 2008; Bunse et al., 2011). Different index decomposition techniques have also been studied (Lin and Du, 2014; Xu and Ang, 2014) in order to highlight different effects in energy intensity.

Capehart et al. (2003) separated the variance between actual and predicted values in two components related to the price variance and the consumption variance. Cesarotti et al. (2009) proposed a methodology for energy budgeting and control that allows to monitor the difference between the budget and actual costs through different indicators designed to distinguish and separate the effects of multiple causes.

Until now, the focus of the analyses has been the identification of the different contributions of the variation in the energy consumption from plant/company level to lower systems level, distinguishing the effects of the system efficiency from the ones related to the energy drivers.

However, considering the diffusion of on-site generation technologies and the growing interest of the industry sector for their application, this paper aims to develop a methodology for energy budget control in this specific complex framework.

This methodology has been developed in response to the demand of a specific company with an on-site generation system, following an empirical approach and building on the systematic methodologies proposed by Cesarotti et al. (2009) and Benedetti et al. (2016).

In comparison with the existing literature, the purpose of the proposed method is to highlight the distinct contributions of sold, purchased and produced energy in the global energy budget, while simultaneously accounting for the difference between predicted and actual value in terms of different prices and amounts of energy.

2. Methodology

In general, the energy used in an industrial plant that has on-site generation can be seen as the contribution of three factors: sold energy, purchased energy and self-produced energy. The energy budget can be seen as the product of the specific energy cost and the total energy consumption.

$$\text{Energy Budget} = \text{Energy consumption} \times \text{specific energy cost}$$

In this case, however, the resulting energy budget can also be seen in another way, focusing the attention on the single contributions cited before. The energy budget will therefore be made up by the corresponding factors as shown in this equation:

$$\text{Energy Budget} = \text{Purchased energy Cost} + \text{Produced energy Cost} - \text{Sold energy Cost}$$

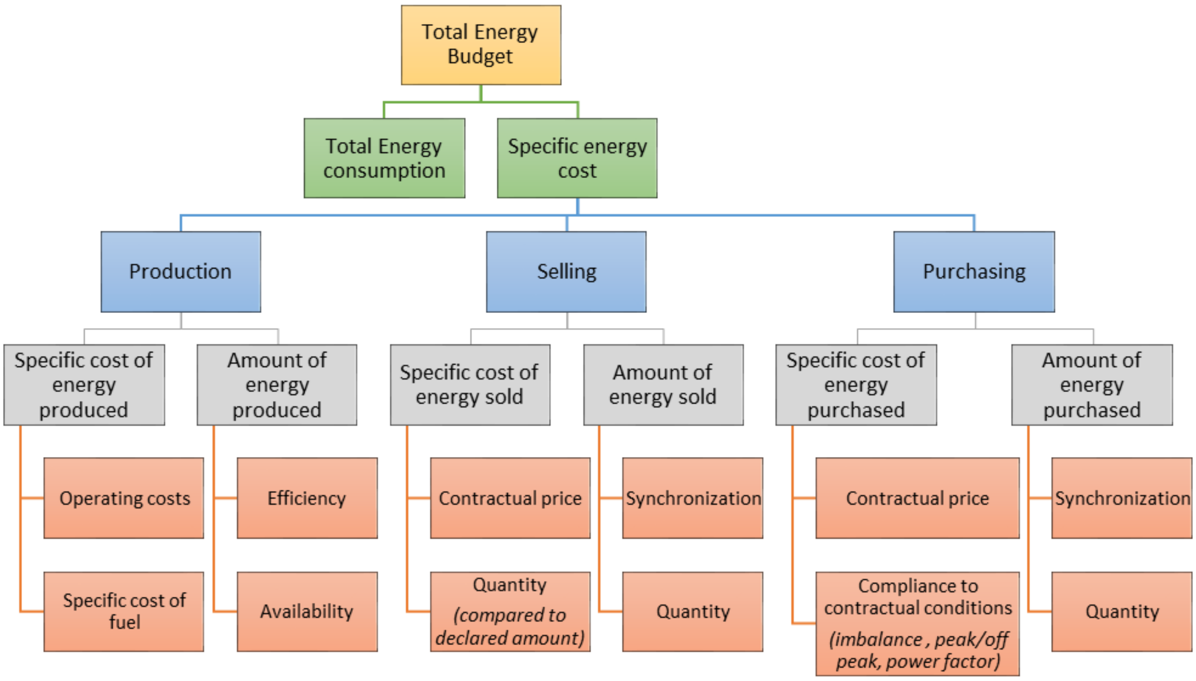

Figure 1: Decomposition of energy budget and factors of influence

Moreover, every term in the equation can be further divided:

Energy Budget =

total purchased energy × specific purchased energy cost

+ total produced energy × specific produced energy cost

- total sold energy × specific sold energy cost

Every term in this last equation is dependent on several factors, as explained in the following paragraph.

With equal energy consumption, the variation of these components will result in a difference in the global specific energy cost of the entire plant.

2.1 Factors of influence

2.1.1 Total energy produced and specific cost of energy produced

The energy produced by the on-site generation system will be directly dependent on the efficiency and on the availability of the system itself. The efficiency is typically linked to the load and it is usually recommended to set the system to a load proximal to the nominal condition in order to grant the best possible performance. Moreover, the deviation from the maximum efficiency can be determined by other causes, depending on the typology of the system itself. For many technologies, certain ambient conditions can cause a performance deficit. The condition of the system itself, linked to the frequency and the accuracy of maintenance, can also affect the efficiency. The actual time of use of the system is subjected to operational choices (functioning hours, programmed maintenance, etc.) therefore the energy produced would not always be constant.

The specific produced energy cost will be affected by other factors, first, the price of the fuel. This will be dependent on the typology of the system and the skills of the operators. In fact, sometimes it is possible to use different variants of fuel. The difference in quality will be reflected on the performance of the system, for example requiring more maintenance operations. On the other hand, the inferior quality of the fuel will mean a lower price. Besides, fuel prices are subjected to the trends of the global market. Palm-oil price is a clear example of this statement: because of the global outcry against its use in the food industry, the prices for this kind of fuel have severely diminished. In addition, the operating costs connected to the on-site generation must be taken into account: energy and resources necessary to the exercise of the system, personnel, maintenance. Finally, there is also the amortization of the price of the system to consider.

2.1.2 Total energy purchased and specific cost of energy purchased

The energy purchased from the grid is equivalent to the instantaneous difference between the energy consumption required by the industrial plant and the energy already produced and available inside the plant. As a result, a variation from the predicted value can be caused by the necessity of an amount of energy different from the prediction or by an asynchronization between demand and on-site production.

The specific cost of energy purchased will be influenced by the supplier and tariff choice. The amount of energy purchased in an industrial plant affects the electricity cost, the higher this is, the lower the specific value stipulated in the contract will be (Benedetti et al., 2015). However, the contractual value seldom is the true one applied to the actual energy purchased. The reason for this is the application of additional costs depending on the nonconformity to the contractual conditions. In particular this is related to exceeding the maximum power employed (peak demand), to an incorrect power factor correction and in general to the lack of a careful management of the site demand. Another important factor is the mechanism of grid balancing. Nowadays, with an increasing number of consumers that are also producers, it has aroused the need for regulations that could enable an integrated energy market. Therefore, operators have now to declare the amount of energy that will be sold or purchased from the grid. The imbalance is always detrimental and will always imply an economic disadvantage.

2.1.3 Total energy sold and specific cost of energy sold

The amount of energy that exceed the demand of the industrial plant is usually sold to the grid. Otherwise, it could be stored through batteries or other storage systems and used in another moment. This amount of energy is therefore affected by the real consumption of the plant and the actual production of the on-site system as well as the synchronization of these two quantities. In fact, it is not always feasible or even convenient to lower the production of the generation system, even if the site demand decreases. The efficiency of the system could decline with a lower load, the act of the regulation itself could be impossible or simply require too much time.

Moreover, the specific cost of energy sold will be influenced by the market conditions and the ability of the person responsible in predicting the amount of energy that will be sold to the grid. In fact, a negative imbalance concerning the declared amount introduced in the electrical grid will result in economic compensations. On the other hand, a surplus in the actual amount sold, will be quantified with a minimum cost, resulting in an inconvenient exchange. Therefore, the two factor influencing the actual cost of energy sold are the balance with the grid and the contractual price.

2.2 Indicators

In order to obtain a better understanding of the situation of the energy budget management in the plant, in this paper are thus presented a series of multi-level indicators. The object of this proposed methodology is the individuation of the different causes of variation from the predicted value. This will help top management, leading to a more conscious strategy as well as making possible to appoint the responsibility to the different centers. The proposed methodology has been created with the aim to provide a clear visualization of the different components that can affect the total energy budget variation.

The total Budget Index, already seen in literature, is divided in two components, one related to the difference in total energy consumption inside the plant (EC, Energy Consumption Index) and the other related to the difference in the global specific energy cost (SC, specific energy cost Index). The two indexes are defined as follows:

B Index = (Bact – Bpred) / Bpred

B Index = EC Index + SC Index

EC Index = [(ECact – ECpred) * SCpred] / Bpred

SC Index = [(SCact – SCpred) * ECact] / Bpred

Where:

Bact and Bpred are actual and predicted energy budget

ECact and ECpred are actual and predicted energy consumption

SCact and SCpred are actual and predicted specific energy costs

It has been decided to not have a third term representing the interaction between this two factor in order not to have a more complex structure already at this level of decomposition. Thus, in the SC Index the effective value of energy consumption is present as opposed to the predicted one, incorporating the interaction between the variations of energy consumption and specific energy cost in this index. This choice is also motivated by the fact that the variation of energy consumption will appear as one of the factor of influence in the decomposition on the following levels.

On the second level of decomposition, the SC Index is then divided in three components, each linked to the different components of the energy budget as described before: produced (EB_{PR}, Energy budget – production Index), purchased (EB_P, Energy budget – purchase Index) and sold (EB_S, Energy budget – selling Index).

SC Index = EB_{PR} Index + EB_P Index – EB_S Index

EB_i Index = [(EB_iact / ECact) – (EB_ipred / ECpred)] * ECact/ Bpred

Where:

$EB_i = Q_i$ x SC_i

Q_i = quantity of energy

SC_i =specific cost

With i = production, selling, purchased

Where EB_iact and EB_ipred are actual and predicted energy budget related to one of the three components of the global energy budget, determined as the product between total energy and specific energy cost of the i-th component.

It is important to notice that the component related to the sold energy is negative because of the opposite nature of the flow of money it has in the global budget. This level of decomposition is useful for understanding what components of the global budget are responsible for the deviation.

However, some deviations in these three terms might be rooted in other ones, and are therefore visible only with an ulterior decomposition. On the third level, every term is divided into four components, considering the impact of the difference in the amount of energy predicted (QD_i, quantity deviation Index), the specific cost (SC_i, specific cost deviation Index), the amount of energy consumption of the plant (ECD_i, energy consumption deviation Index) and the interaction between all three (Int_i, interaction Index).

EB_i Index = QD_i Index + SCD_i Index + ECD_i Index + Int_i Index

With i = production, selling, purchase

QD_i Index = [(Q_i act – Q_i pred) * SC_i pred] / ECpred * (ECact/ Bpred)

SCD_i Index = [Q_i pred * (SC_i act – SC_i pred)] / ECpred * (ECact/ Bpred)

ECD_i Index = (Q_i pred * SC_i pred) * (1/ECact – 1/ECpred) * (ECact/ Bpred)

Int_i Index = EB_i Index – (QD_i Index + SCD_i Index + ECD_i Index)

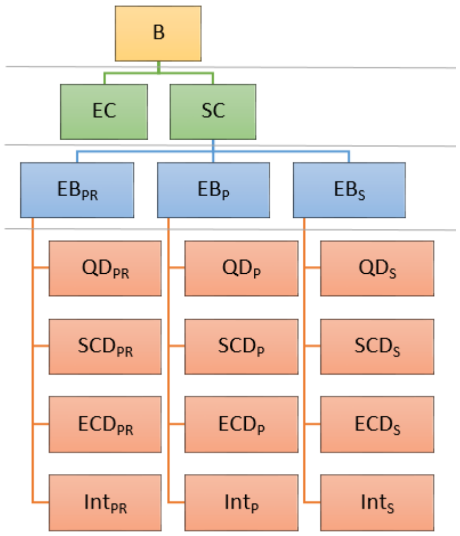

Figure 2. Budget index decomposition at different levels

At this level it is possible to observe more accurately the reason of the global variation in the specific energy cost of the plant. In fact, causes that were invisible on the upper level because of the single deviations interfering with each other can now be noted.

In conclusion, this methodology allows to identify for each cost/responsibility center an indicator for the energy performance.

A synthetic representation of the structure of the decomposition is shown in Figure 2.

3. Case study

After having been mathematical validated through a simulation, the presented methodology has been applied to the case study of an Italian manufacturing company in order to prove its usefulness and its validity in the specific case. The company produces consumer goods and is classified as energy-intensive. The plant object of the present study is provided with a cogeneration system (a motor fueled with palm oil) and is connected to the electricity grid (allowing the organization to sell extra energy produced by the cogeneration system or to buy electricity when needed).
The following cost/responsibility centers have been identified in the organization structure:

- Whole plant;
- Energy purchasing office (responsible for purchasing electricity and palm oil);
- Cogeneration system.

The first center is responsible for the energy consumption of the plant, while the last two are responsible for the specific cost of energy of the company. In particular, the second one is responsible for the contractual conditions related to the purchase of electricity from the grid and the palm oil. The third one is responsible for the availability and efficiency of the cogeneration system, therefore is connected to the amount of energy produced and the eventual extraordinary maintenance that can affect the specific cost of production.

The updating frequency for the performance indicators is set monthly. Thus, the system can only be used for strategic control purposes at the moment.

For every month the data regarding the actual flows of energy (sold, produced, purchased and consumed) as well as the actual costs of the three components of the budget (purchased energy cost, produced energy cost, sold energy cost) have been recorded and confronted with their predicted values. The data used are not published to ensure the privacy of the company.

Thought the definition of the previous indicators a budget performance control matrix has been created, allowing a global and immediate visualization of the energy budget performance of the plant. The cells of the matrix are colored in red if the indicator shows a decrease of the performance over a fixed threshold value, in green if the indicator shows an improvement of the performance over a fixed threshold value and in grey if the difference is considered negligible.

The predicted budget values have been set for the new fiscal year (2015 - 2016), considering predictions for energy prices and amounts.

The budget performance control matrix has been updated every month, leading to the individuation of several anomalous trends in the performance.

In order to provide a general understanding of its use, some interesting examples of the application of the performance control matrix are now reported.

By observing the matrix (Fig. 3), it is apparently possible to detect an overall improvement of the energy budget trend. While in the second half of 2015 there have been three months with an actual budget superior to the predicted value, in the first half of 2016 the actual values have been inferior to the predictions, as shown by the succession of red cells in the second half of 2015 and of green cells in the first half of 2016.

	B Index	SC Index	EC Index	EB pr	EB s	EB p
Jul-15	-0,21%	-0,83%	0,62%	-0,57%	0,21%	-0,48%
Aug-15	1,49%	3,06%	-1,53%	1,15%	0,21%	1,66%
Sep-15	0,34%	-0,52%	0,86%	-0,65%	0,38%	-0,25%
Oct-15	0,64%	0,42%	0,22%	-0,04%	0,47%	0,00%
Nov-15	0,38%	0,83%	-0,44%	0,42%	0,23%	0,18%
Dec-15	9,03%	8,14%	0,82%	-1,33%	0,26%	9,28%
Jan-16	0,14%	0,22%	-0,09%	0,06%	0,11%	0,06%
Feb-16	-6,55%	1,05%	-7,52%	-1,16%	0,72%	1,42%
Mar-16	0,35%	0,46%	-0,10%	0,10%	0,31%	0,05%
Apr-16	-6,43%	-3,46%	-3,08%	-1,90%	-0,12%	-1,33%
May-16	-6,33%	-9,95%	4,02%	-5,83%	1,30%	-5,83%
Jun-16	0,23%	0,51%	-0,28%	0,18%	0,18%	0,16%

	Production				Selling				Purchase			
	QD pr	SC pr	EC pr	Int pr	QD s	SC s	EC s	Int s	QD p	SC p	EC p	Int p
Jul-15	0,68%	-0,67%	-0,57%	0,00%	0,07%	2,76%	-0,04%	-2,58%	0,00%	-0,39%	-0,09%	0,00%
Aug-15	-1,08%	1,10%	1,14%	-0,02%	0,13%	3,26%	0,26%	-3,44%	0,99%	0,00%	0,65%	0,02%
Sep-15	0,01%	0,00%	-0,66%	0,00%	-0,29%	0,29%	-0,08%	0,46%	0,01%	0,02%	-0,28%	0,00%
Oct-15	0,18%	0,00%	-0,22%	0,00%	0,01%	0,04%	-0,03%	0,45%	0,02%	0,00%	-0,02%	0,00%
Nov-15	0,00%	0,10%	0,31%	0,00%	0,14%	1,90%	0,05%	-1,87%	0,01%	0,00%	0,18%	0,00%
Dec-15	-7,92%	8,02%	-0,71%	-0,73%	0,05%	1,71%	-0,06%	-1,45%	13,72%	-2,54%	-0,17%	-1,73%
Jan-16	0,00%	-0,01%	0,06%	0,00%	0,03%	-0,09%	0,00%	0,17%	0,03%	0,00%	0,03%	0,00%
Feb-16	-7,43%	-0,28%	7,15%	-0,60%	-1,21%	-3,01%	1,02%	3,92%	0,03%	0,00%	1,39%	0,00%
Mar-16	0,03%	-0,02%	0,09%	0,00%	0,07%	-0,65%	0,01%	0,88%	0,03%	0,00%	0,03%	0,00%
Apr-16	-1,96%	-3,14%	3,30%	-0,10%	0,19%	0,15%	0,50%	-0,96%	-0,03%	-1,53%	0,28%	-0,04%
May-16	3,74%	-5,62%	-3,81%	-0,13%	0,02%	-0,58%	-0,70%	2,57%	-1,70%	-3,67%	-0,92%	0,46%
Jun-16	0,01%	0,02%	0,14%	0,00%	0,10%	-0,60%	0,02%	0,65%	-0,01%	0,00%	0,16%	0,00%

Figure 3. Performance control matrix

While observing the lower levels indicators it is also possible to recognize the reasons for this discrepancy. The main instances are in December 2015, February 2016, April 2016 and May 2016.

In all these months except for February, the reason for the variation is ascribable to a different specific energy cost. In February, instead, the reason is a lower energy demand from the plant, due to unexpected lower production volumes (EC = -7,52%, green cell), while the amount of energy produced and sold decreased (QDpr = -7,43%, green cell; QDs = -1,21%, red cell). It is interesting to observe that the decrease in energy consumption has the effect to reduce the impact of the lower production.

In December the specific energy cost increased while the energy consumption remained almost the same (SC = + 8,14%, EC = +0,82%). The values of EBpr and EBp (-1,33% and +9,28%) indicates that a difference in the purchase of energy together with a difference in the production is the main cause of the variation. Indeed, a scheduled maintenance for the cogeneration system has caused a lower number of functioning hours due to the discovery of other necessary procedures to do. This is visible in the increment of the specific cost of energy produced (SCpr = +8,02%), the decrease of the amount produced (QDpr = -7,92%) and the consequent increase of energy purchased from the grid (QDp = +13,72%), more expensive than the alternative.

In April and May, instead, the specific energy cost of the plant was lower (respectively SC = -3,46% and -9,95%). In April a lower demand (EC = -3,08%) allowed the cogeneration system to produce less and at a lower cost (EBp = -1,90%). In addition to this, the specific cost of energy purchased was lower (SCp = -3,67%). In May, in order to recuperate the volumes not produced in the month before, the plant worked more hours (EC = + 4,02%). However, a better management of the cogeneration system has allowed to have a more efficient synchronization between demand and production, thus requiring less purchase from the grid (EBpr = -5,83% and EBp = -5,83%). Moreover, the amount of energy produced increased but the specific cost of produced energy decreased (QDpr = +3,74%, SCpr = -5,62%).

4. Conclusions and future developments

A new methodology has been proposed to enable the control of energy budget in plants with on-site generation systems, through establishing a series of indicators at different levels.

In order to test its robustness and its usefulness this methodology has also been applied to a real case study of an Italian manufacturing company.

The case study has been successful, demonstrating that the methodology proposed can be successfully applied to the energy budget control in manufacturing plants with similar configuration of on-site generation systems.

Anyway, in order to assess its general validity and to create a refined and general methodology it is necessary to test the developed tool on more case studies. In particular, it would be recommendable to test its efficacy in companies with different configuration of on-site generation systems. Further studies should also be conducted to test the tool with a higher frequency for data acquisition.

Another future development is represented by the implementation of an automatic analysis of the indicators in order to directly provide the company with the interpretation of the variation in the budget, which as of now is helped by the color-coding of the matrix.

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