Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 3112 – 3117

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Assessing and improving Compressed Air Systems' energy efficiency in production and use: findings from an explorative study in large and energy-intensive industrial firms

Miriam Benedetti[a*], Ilaria Bertini[b], Francesca Bonfà[b], Silvia Ferrari[b], Vito Introna[c], Domenico Santino[b], Stefano Ubertini[d]

[a]*Department of Industrial Engineering, "Tor Vergata" University of Rome, Via del Politecnico, 1, 00133, Rome, Italy*
[b]*Energy, New Technology and Environment Agency (ENEA), Via Anguillarese 301, 00123 Rome, Italy*
[c]*Department of Enterprise Engineering, "Tor Vergata" University of Rome, Via del Politecnico, 1, 00133, Rome, Italy*
[d]*DEIM - School of Engineering, University of Tuscia, Largo dell'Universitá s.n.c., 01100 Viterbo,*
[*]*Corresponding author email: miriam.benedetti@uniroma2.it*

Abstract

Compressed Air Systems (CAS) are one of the most common and energy intensive utilities in industry, representing up to 10% of the industrial energy needs. Nevertheless, benchmarks currently available are usually based on nominal data and referred to the quality of the design, while there are still no available benchmarks based on measured industrial data, taking into consideration actual operating conditions, and referred to compressed air production and, most of all, use. In accordance with the Italian transposition of the European Directive 2012/27/EU (i.e. Legislative Decree 102/2014) large and energy-intensive enterprises have been asked to perform mandatory energy audits in 2015. In this context, a data collection focused on CAS has been carried out by means of a semi-structured questionnaire in the form of a spreadsheet. First data analyses performed and relative findings are here illustrated, together with the next steps for the creation of reliable sectorial and cross-sectorial benchmarks.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Energy Efficiency, Compressed Air Systems, Directive 2012/27/EU, energy benchmarking.

1. Introduction

With the promulgation of the Directive 2012/27/EU, a common framework of measures for the promotion of energy efficiency has been established in order to ensure the achievement of the European Union's energy efficiency improvement target of a 20% reduction of current primary energy consumption by 2020, and to pave the way for further energy efficiency improvements beyond that date. In this context, CAS play a strategic role in order to achieve the always more compelling objective of reducing the

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.653

industrial energy consumption in Europe as well as in the rest of the world [1, 2], due to their large diffusion in industrial plants [3] and to their energy intensity [3-6].

Italy has transposed the cited European Directive into national law by issuing the Legislative (Lgs.) Decree n°102 of the 4th July 2014. According to Art. 8 of such Decree, the large [8] and energy intensive (i.e. enlisted in the ad hoc list for the electricity sector of Cassa Conguaglio) enterprises must undergo energy audits on their plants at least every four years, starting from the first deadline that was 5 December 2015.

The implementation of the Lgs. Decree 102/2014 in 2015 has therefore been the perfect opportunity to gather CAS-related data in order to assess the current energy efficiency level of compressed air production and use in Italian industry, to define effective benchmarks and to enhance knowledge and best practices transfer among undertakings, thus contributing to the increment of CAS's energy efficiency. Data gathered were not limited to CAS, but first analyses were conducted on these systems due to their relevance from an energy efficiency point of view, as previously highlighted. As a matter of facts, only a few relevant and reliable benchmarks are available in the scientific and technical literature, as for example [4, 5, 8-10], but they are usually referred only to the production phase and are generally calculated in nominal conditions, not considering system's deterioration over time, specific operating conditions and also the influence of set points and demand fluctuations. This makes such information very unhandy and often confusing for companies. In such a context, a series of studies has been set up aimed at helping companies in the complex assessing, benchmarking and improving CAS's energy efficiency, and at providing them with accessible, easy and effective tools. Italian data have thus been used as a first data set to design such tools, and obtained results can be applied to the international context and extended where possible. The study presented in this paper is then the first step of a broader research framework, and the process for collecting data regarding CAS's energy efficiency is described, along with the data analysis methodology used and first findings

2. Methodology

Data analyses have been initially limited to the following nine industrial sectors, selected for their intensive use of compressed air, on the basis of existing literature [9, 10]: manufacture of basic metals, chemicals and chemical products, basic pharmaceutical products and pharmaceutical preparations, fabricated metal products except machinery and equipment, motor vehicles, plastics products, textiles, food products, paper and paper products [11].

Target organizations have been asked to complete a voluntary semi-structured questionnaire in the form of a spreadsheet, and to submit it together with the mandatory documentation. The questions asked in the spreadsheet are summarized in Table 1. The collected variables are production volumes, total electrical consumption, indicated as kWhe TOT, amount of energy consumed for the production of compressed air, indicated as kWhe CAS, and value of the main energy driver. Such variables are all referred to the year 2014. Given the exploratory nature of this first study, no power analysis and sample size calculation was performed in a preliminary fashion.

Data analyses have been mainly performed on derived variables calculated as follows:

- The ratio between the amount of energy consumed for the production of compressed air and the total electrical consumption (kWhe CAS/kWhe TOT);
- The ratio between the amount of energy consumed for the production of compressed air and the production volumes, generally expressed as tons of final product (kWhe CAS/t);

The ratio between the amount of energy consumed for the production of compressed air and the value of the main energy driver, generally expressed as m^3 of compressed air produced (kWhe CAS/m^3).

First of all, the distribution of the collected variables has been analyzed and its normality has been tested with the Anderson-Darling test [12]. Then, variables have been examined by calculating descriptive statistics (frequencies, percentages, averages, medians, standard deviation and confidence of intervals at 95%). To compare industries' sub-sectors, the Welch's One-Way ANOVA test [13] has been used to evaluate differences in the means of continuous variables. This test has been selected for its wide applicability, as it does not assume data sets to be normally distributed if they have an adequate size or to have similar standard deviations. Statistical tests have been performed accepting a probability value (P-value) ≤ 0.05. Such analyses have been performed for each industry and also repeated for industries' subgroups limited to those that have provided continuously measured data, except for the Welch's One-Way ANOVA test due to the restricted samples size. Analyses regarding the kWhe CAS/m^3 derived variable have only been conducted on subgroups, as non-measured data seemed useless in this case, and cross-sectorial, in order to avoid problems due to restricted sample size.

3. Data analysis results

In this section, the results of the data analysis are presented in details for the manufacture of basic metals in order to give a complete description of the presented methodology's application, while they are only briefly summarized for the other analysed sectors.

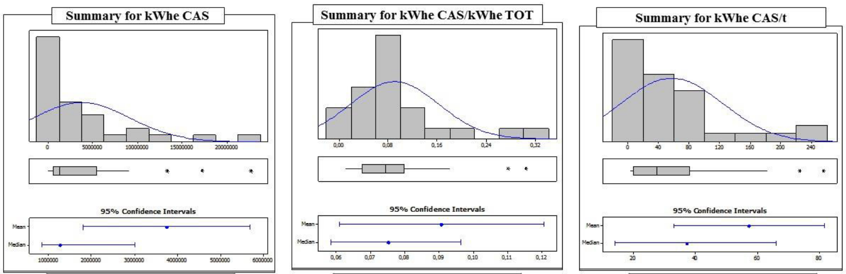
For the manufacture of basic metals, 223 questionnaires have been analysed. Of the corresponding 223 plants, 195 gave an estimation or a measure of the value of the amount of energy consumed for the production of compressed air. The highest percentage of questionnaires was returned by undertakings belonging to the casting of metal sub-sector (over 40%) and the rest of them belongs to other 4 sub-sectors or did not declare it (over 20%). Table 1 summarises the percent breakdown of responses to each question.

Table 1. Questions and percent breakdown of responses

Questions	Possible answers	Percent
Methodology adopted for estimating total electrical consumption	Calculated from energy bills	17%
	Spot measures	4%
	Continuous measures provided by dedicated meters	70%
	Undeclared	9%
Methodology adopted for estimating the energy consumed for the production of compressed air	Calculated from energy bills	69%
	Spot measures	3%
	Continuous measures provided by dedicated meters	14%
	Undeclared	14%
Please indicate the main energy driver you use to evaluate the performance of your compressed air system	Compressed air production	35%
	Others	1%
	Undeclared	64%
Methodology adopted for estimating values related to the main energy driver for your compressed air system	Calculated on the basis of nominal system's parameters or of physics	28%
	Spot measures	1%
	Continuous measures provided by dedicated meters	4%
	Undeclared	67%

In the plots shown in Figure 2, results for normality test and descriptive statistics of main variables and derived variables are represented for groups of data comprehending continuous measures only (see Figure 3 for a summary of the results obtained for the whole sample). Only plants measuring production volumes in weight have been considered in order to analyze the ratio between the amount of energy consumed for the production of compressed air and the production volumes due to the fact that they are above 90% of the total.

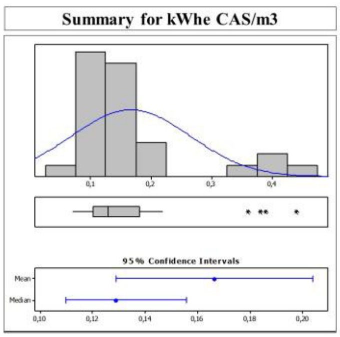
The results of Welch's One-Way ANOVA are not plotted for sake of brevity, but they show that there is no significant difference in the mean value of the analysed variables and derived variables of plants belonging to different sub-sectors.



Anderson-Darling Normality Test	kWhe CAS	kWhe CAS/kWhe TOT	kWhe CAS/t
A-Squared	3.58	1.52	2.23
P_value<	0.005	0.005	0.005
Mean	3745498	0.090615	57.379
StDev	5360225	0.072321	66.262
Variance	2.87320°+13	0.005230	4390.615
N	32	25	31
Minimum	36223	0.010237	2.168
1° Quartile	537003	0.037904	7.292
Median	1281079	0.075276	37.353
3° Quartile	5444911	0.105878	81.007
Maximum	22700889	0.303860	255.452

Fig. 2. Manufacturing of basic metals: normality test and descriptive statistics of main variables and derived variables for groups of data comprehending continuous measures only.

The main results of the data analysis are summarized in the matrix shown in Figure 4, reporting the various industries on columns and questions, variables and derived variables on rows. The green colour in the cells of the matrix means that values of answers, variables and derived variables highlight a satisfying amount of data collected or a relevant probability of profitably implement energy efficiency measures. Red colour means the opposite. Median values rather than means have been analysed, in order to obtain more reliable results, as several industries showed a relevant amount of outliers that have still got to be interpreted. The last row of the matrix shows the impact of the amount of energy consumed by CAS in each industry on the national industrial energy consumption (calculated according to data reported by [14]). In the following Figure results of the kWhe CAS/m^3 derived variable are reported.



Anderson-Darling Normality Test	
A-Squared	3.20
P_value<	0.005
Mean	0.16646
StDev	0.09840
Variance	0.00968
N	29
Minimum	0.07034
1° Quartile	0.10472
Median	0.12900
3° Quartile	0.18108
Maximum	0.44007

Fig. 3. Results of the analysis conducted on the ratio between the amount of energy consumed for the production of compressed air and the compressed air produced.

			Basic metals	Chemicals	Pharmaceutical	Fabricated metal products	Motor vehicles	Plastics products	Textiles	Food products	Paper
AMOUNT OF DATA COLLECTED		Number of analysed questionnaires	223	208	105	315	72	228	132	385	95
		Number of plants continuously measuring kWhe TOT	156	134	64	191	47	151	82	265	71
		Number of plants continuously measuring kWhe CAS	32	30	10	19	7	17	6	38	9
		Number of plants continuously measuring m3 of compressed air produced	9	16	6	6	7	5	3	11	2
PROBABILITY OF PROFITABLY IMPLEMENT ENERGY EFFICIENCY MEASURES	GROUPS OF DATA COMPREHENDING CONTINUOUS MEASURES	kWhe CAS	1281079	1629138	924103	504000	1558550	785342	521500	951221	38812468
		kWhe CAS/kWhe TOT	0,08	0,12	0,05	0,10	0,10	0,07	0,05	0,07	0,04
		kWhe CAS/m3	0,13	0,12	0,16	0,13	0,13	0,00	0,10	0,14	0,17
		kWhe CAS/t	37	16	831	35	255	143	51	21	23
	WHOLE SAMPLE	kWhe CAS	506920	517216	410253	272411	530982	341521	245410	285488	459228
		kWhe CAS/kWhe TOT	0,07	0,08	0,05	0,09	0,12	0,06	0,06	0,06	0,04
		kWhe CAS/t	44	24	1405	59	92	50	119	18	18
		Incidence of CAS energy consumption on national industrial energy consumption	1,23%	0,97%		1,23%	0,27%	0,32%	0,19%	0,58%	0,25%

Fig. 4. Summary of the main results of the data analysis for all analyzed industries.

4. Discussion

Results from the data analysis led to the drawing of a first set of findings. First of all, the dramatically low percentage of plants measuring the kWhe CAS as well as the amount of produced compressed air is an effective indicator of the still too little attention paid to energy management in Italian industrial plants. Despite the high energy cost related to compressed air production, energy measuring, controlling, budgeting and forecasting are still rarely performed, not even in highly energy intensive systems. Therefore, the development of energy measuring systems should be considered as a priority over the next few years. CAS appear to be a significant energy use in most industries, as the kWhe CAS/kWhe TOT derived variable ranges from 4% to 12%, with a mean value across different industries of about 7%. They also cover a significant percentage of the national industry consumption (i.e. a total of 5% considering all analyzed industries).

The kWhe CAS/t derived variable seems to be a promising indicator for CAS energy efficiency within a single industry, as it appears to have a non-scattered distribution, while it cannot definitely be used to compare different industries. This is probably due to different processes required by different products. Looking at Figures 2 and 3, it is possible to observe how plants showing anomalous behaviors are easily identifiable and also represent a small percentage of the total. Once the energy efficiency situation of these plants will be analyzed, evaluating whether different performances are due to different systems' efficiency or to different operational parameters' settings, it will be possible to repeat the analysis on the same sample and verify the reliability of those values and distributions as benchmarks.

The kWhe CAS/m^3 is instead a good cross-sectorial indicator of the energy efficiency in the production of compressed air, but it does not allow measuring the energy efficiency in the consumption of such a vector. An indicator such as the amount of compressed air used to produce a single ton of product would be useful, but the restricted number of plants measuring compressed air still does not allow its calculation. Anyway, Figure 3 shows that the range of the kWhe CAS/m^3 value is slightly above the one proposed by [8], which is probably due to the fact that the latter does not consider real use operating conditions. There is also a small number of plants showing a much higher range, probably because they have different pressure requirements (to be confirmed through deeper analyses).

5. Conclusions and future developments

First findings from an explorative study aimed at assessing CAS's energy efficiency and defining reliable and robust benchmarks have been presented. On the average, less than 20% of analyzed plants measure kWhe CAS and about 7% of them measure m^3 of produced compressed air. CAS appear to be a significant energy use in most companies, covering on average the 7% of kWhe TOT. Most promising benchmarking indicators for both compressed air production and use and their calculation have been illustrated, along with their first application to a selected number of industries. By refining and completing the presented analysis (also using its results to identify more specific information to be gathered) and through the proposed methodology, it will be possible to define cross-sectorial and industry-specific CAS energy efficiency benchmarks, enabling and enhancing a more efficient knowledge and best practices transfer among undertakings.

Acknowledgements

This work is part of the Electrical System Research, implemented under Programme Agreements between the Italian Ministry for Economic Development and ENEA, CNR, and RSE S.p.A. The authors would like to thank all the companies that have kindly provided data and supported the project. Warm thanks also to Green Energy Plus S.r.l. that has provided useful feedbacks during the whole project.

References

[1] Introna V, Cesarotti V, Benedetti M, Biagiotti S, Rotunno R. Energy Management Maturity Model: an organizational tool to foster the continuous reduction of energy consumption in companies. *J Cle Prod* 2014;83:108-117.
[2] Benedetti M, Cesarotti V, Introna V, Serranti S. Energy consumption control automation using Artificial Neural Networks and adaptive algorithms: Proposal of a new methodology and case study. *Appl Energ* 2016;165:60-71.
[3] Radgen P, Blaustein E. Compressed Air Systems in the European Union: Energy, Emissions, Savings Potential and Policy Actions. 2001.
[4] Phelan P, Chau D, Sarac H., Kaya D. Energy conservation in compressed-air systems. *Int J Energ Res* 2002;26:837–849.
[5] Saidur R, Rahim N, Hasanuzzaman M. A review on compressed-air energy use and energy savings. *Renew Sust Energ Rev* 2010;14:1135-1153.
[6] Dindorf R. Estimating Potential Energy Savings in Compressed Air Systems. *Procedia Engineering* 2012;39:204-211.
[7] European Commission. *The new SME definition, User guide and model declaration.* 2005.
[8] European Commission. *Reference document on Best Available Techniques for Energy Efficiency*. 2009.
[9] Anglani N, Mura P. *Optimization opportunities in compressed air production, distribution and use of compressed air in most relevant sectors* (Opportunità di ottimizzazione dei consumi nella produzione, distribuzione, utilizzo dell'aria compressa nei settori industriali più sensibili). ENEA, 2010.
[10] U.S. DoE. *Compressed Air Challenge. Improving compressed air system performance, a sourcebook for industry*. 2003.
[11] EUROSTAT. *NACE Rev.2, Statistical Classification of economic activities in the European Community*. 2008
[12] Anderson T W, Darling DA. Asymptotic theory of certain "goodness-of-fit" criteria based on stochastic processes. *Ann Math Stat* 1952;23:193–212.
[13] Welch BL. The generalization of "Student's" problem when several different population variances are involved. *Biometrika* 1947;34(1–2):28–35.
[14] TERNA. Electrical consumption in Italy, available at http://www.terna.it/ [accessed 29 May 2016].

Biography

Miriam Benedetti is a doctoral researcher in Industrial Engineering at University of Rome "Tor Vergata". Her main research interests are Industrial Energy Management, Industrial Sustainability, Machine Learning Techniques, Energy Services.