Assessing the contribution of energy saving technologies: the case study of variable speed drive air compressors

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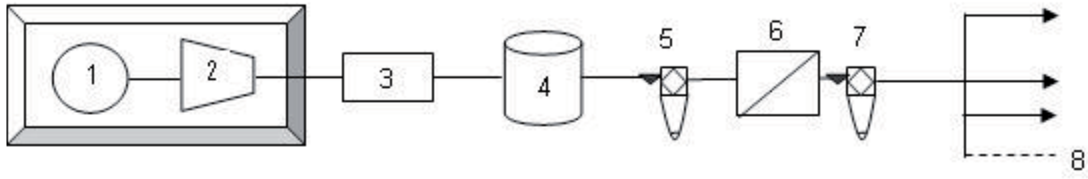
Abstract
After the adoption of the 2006/32/EC Directive on energy end-use efficiency and energy services, the monitoring and evaluation of energy efficiency measures and actions have become a very urgent matter, but still the effectiveness of using top-down versus bottom-up approach is a hot topic for the experts. This paper aims at contributing in favour of the role of bottom-up methodologies of energy savings, bringing to the front the case of one specific technology: use of variable speed drives for air compressors, compared to fixed speed motors, with a load-unload technique. A simplified procedure for evaluating and monitoring the effects of such technological replacement is reported, potentials and drawbacks of a simplified assessment procedure are analyzed and, in terms of a case study, projections of potential savings in the Italian industry (i.e. the mechanical sector, equivalent to the NAICS[1] 3335 sector) are proposed as a way of harmonizing top-down and bottom-up approaches.

Introduction
Directive 2006/32/EC on energy end-use efficiency and energy services (ESD) has made the monitoring and evaluation of energy efficiency measures and actions a very urgent matter to be faced. It is urgent because international agreements on climate change, such as the Kyoto protocol, are binding obligations and the annex B countries have to manage their emission reduction targets with manifold strategies and measures in very tight times: energy efficiency is one of those instruments. At European level an outstanding number of activities have been started: EU funded projects aiming at delivering general procedures for the evaluation of energy savings (i.e. the EMEEES project), Standardization Bodies (such as CEN/Cenelec and ISO) setting up technical forum and groups of experts to deal with standards and common methodologies and each Member State individually managing the international obligations towards their energy and emission reductions targets. Still, the effectiveness of using top-down versus bottom-up approach is a hot topic for the experts.

In Italy, for instance, energy distributors have updated annually obligations aiming at achieving, from 2008 through 2012, a cumulative primary energy saving of 21 Mtoe (ton of oil equivalent, 41.86 GJ). Project savings are evaluated by means of several bottom up procedures that must be approved by the Regulatory Authority for electricity and gas, AEEG [Pavan, 2005] [AEEG, 2008]. Energy efficiency projects are thus granted by the so called white certificates. While energy intensive industries, which fall under the scope of other Directives such as the IPPC[2], do not seem to benefit from the application of such projects, because the procedures set in place sofar deal with actions not suitably targeted to them [AEEG, 2008], small and medium enterprises, as well as the civil sector, represent an interesting target for the ESD.

1. North American Industry Classification System

2. Integrated Pollution Prevention Control



Nomenclature: 1motor, 2 compressor, 3 measurement system, 4 tank, 5-7 filters, 6 dryer, 8 users

Figure 1. Simplified scheme of the load/unload (on/off control) configuration

The measurement and verification procedures, set in place so far in Italy, allow to account for savings, therefore for the accruing of the white certificates, with deemed[3] and analytical methods [Pavan, 2005]. Besides, lump-sum methods [Pavan, 2005], feasible by means of energy monitoring plans, are also admitted. These tools state how to evaluate the savings due to several listed actions on energy efficiency. One certificate corresponds to the saving of one toe of primary energy. This paper aims at contributing to bottom-up methodologies of energy savings, in particular of one specific technology: variable speed drives for air compressors. A simplified procedure for evaluating and monitoring the effects of such technological replacement is reported, potentials and drawbacks of a simplified assessment procedure are analyzed and, in terms of a case study, projections of potential savings in the Italian industry are proposed as a way of harmonizing top-down and bottom-up approaches.

Bottom up methodologies

In a bottom-up approach[4] the quality of results depends both on the accuracy of input data, on the reliability of the applied bottom-up methodology itself, but also on being the method easy applicable and verifiable, just to cite few.

The methodology, here presented, applies to a stand-alone air compressor rotating system and must satisfy two paramount requirements: (i) to minimize the amount of data collected by the proponent, (ii) to use the so-called analytical or engineering procedure, where a model must be defined by means of its measurable and not measurable parameters, possibly with no resort to any corrective unexplained factor, according to the M&V (measurement and verification) methods defined in [Pavan, 2005].

Although the two requirements mentioned above entail approximations in the assumptions, the positive feature is that they match the need of using very simple procedures in the development, validation and control stage, with no risk of over-estimating the potential saving.

Two configurations of plant will be compared: the new one, featuring a variable speed drive (VSD) compressor versus the old, less efficient one, featuring a load/unload controlled compressor (baseline). In this paper only the monitoring phase, which completes the procedure once the VSD is operated, will be reported. The *a priori* feasibility evaluation study -and related to acquired data- are reported in a previous paper [Anglani, 2007]. Nevertheless, the fundamental output will be here reported because they are instrumental for the completeness of the whole M&V procedure.

Before focusing on the procedure itself, the operating conditions of the compressed air system before and after the replacement have to be known. The new energy saving configuration has to be monitored in its operational parameters and compared to the old one: the terms of such comparison need to be set. Once the sampling period is settled, some information must be gathered: (i) the technical data sheet of the machine from the manufacturer (the list is reported in the tables below); (ii) the amount of compressed air over the sample period (or the electricity consumption) and (iii) the operating hours. For the replaced configuration, information must be inferred from a preliminary survey campaign, accordingly to the requirements reported in details in [Anglani, 2007]. Along with the air demand from the network, the pre-assessment (previous to this monitoring stage) needed to gather information on the type and efficiency of the compressor at different load factors (usually at rated and at unload[5] conditions). Hence, data regarding working hours and operating activities of the load/unload controlled compressor were useful to build up the profile of time-dependant demand.

COMPARING SCHEMES AND INSTALLATIONS

The evaluation methodology on energy savings takes into account the energy consumption of two alternative configurations (reported in Figures 1 and 2) to regulate the air flow rate according to the compressed air requirement. Figure 1 represents the standard system configuration (baseline), while Figure 2 shows the new VSD based configuration (energy saving alternative). Notice that the baseline of the old configuration has been optimized, by allowing the use of a storage tank to downsize the compressor's capacity with respect to the size of the demand.

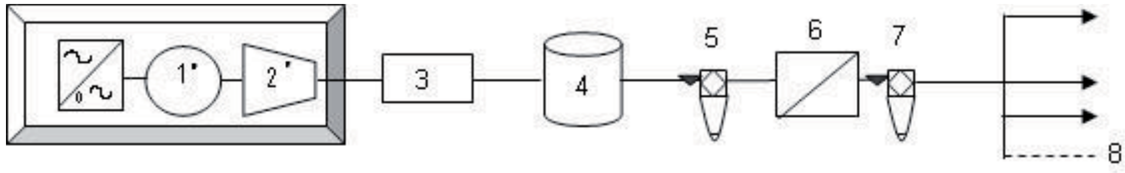
In details, Figure 2 reports the new system, where the motor "1" of Figure 1 is substituted for the variable speed drive, made up by a power converter (inverter) "0" and a related new motor "1' ". In summary the blocks "1" and "2" of Figure 1, as a whole, are replaced by the new machine represented by the blocks "0-1'-2' ".

The load fluctuation, due to variable air needs, is satisfied by smoothly changing the speed of the compressor. There is a continuous adjustment of the compressed air output by a proportional regulation of the motor/compressor speed to match the compressed air demand. Lower speeds are set when the air demand is lower: nevertheless the compressor always works at its best performances and the overall efficiency is far better

3. These are also known as default unitary energy savings and these values are set ex-ante.

4. According to the ESD, Annex IV definition.

5. Also known as off load or no load conditions.



Nomenclature: 0 inverter, 1' motor 2' compressor, 3 measurement system, 4 tank, 5-7 filters, 6 dryer, 8 users
The 0-1' blocks represent any type of variable speed drive system

Figure 2. Simplified scheme of the VSD compressed air system configuration.

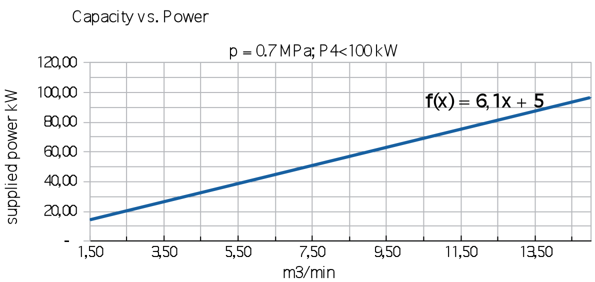


Figure 3. Proposed universal curve, relating capacity and supplied electric power (p_{set}=0.7 MPa, P_4 < 100 kW)

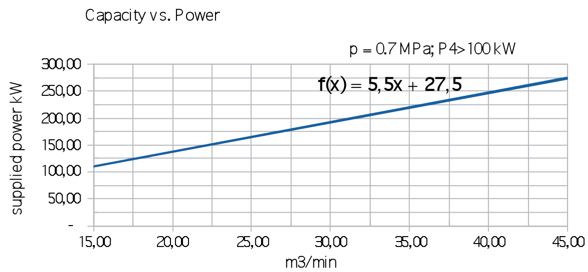


Figure 4 Proposed universal curve, relating capacity and supplied electric power (p_{set}=0. MPa, P_4 > 100 kW)

than the one in the on/off (load/unload) mode. This is due to the fact that in this latter case the compressor runs at its rated conditions, to fill up the tank, but it is idling (still consuming energy) when there is no need to operate.

It is paramount to mention that this procedure only deals with the compressor itself and not with the whole system of devices, that are assumed to be taken under consideration in a previous optimization. To optimize the whole system is a wise step to consider from the perspective of the effectiveness and completeness of any energy saving action and investment, nevertheless it is not as common as should be. For the sake of the proposed procedure is anyway insignificant, although it could increase the amount of savings.

The scheme applies to rotating compressors from 30 kW upwards (several hundred kWs). The whole procedure (the a priori evaluation and the monitoring phase) requires two sampling periods: at least one typical working week each; although a longer period, such as a whole quarter of a year, would be the optimal choice. The first time span is identified as “SP1”, sample period 1, chosen when the load/unload compressor is still operating (configuration of Figure 1). In this case the comparison is carried out to demonstrate that a VSD machine would perform better. If the feasibility is demonstrated, then, once the replacement takes place, the monitoring second phase is scheduled. The second time span is called SP2, sample period 2. Over this period the VSD compressor, replacing the old load/unload machine, is monitored (VSD configuration) and its performances are compared with the old system data. The evaluation procedure over SP1 has already been illustrated in details in [Anglani, 2007], therefore here we will be referring to some of those results. In the following the procedure to assess the real energy savings of the VSD configuration is reported.

The novelty of the proposed method deal with the idea to rely on 7 *universal curves* and *equations* (2 curves for 3 set pressure levels, plus one, according to the size of the machine: below 100 kW and above) to assess missing data in the comparisons.

In Figures 3 and 4 two curve excerpts for the operating pressure of 0.7 MPa (7 bar), in the whole range of considered power (above and below 100 kW), are reported below because they are functional to the proposed case study. The curves on Figures 2 and 4 describe the input electric power of the new VSD compressor (P_4, full package[6]) as a function of the capacity (q_4 free air delivery[7], m^3/min) and they have been derived from a careful examination and comparison of technical data sheets from manufacturers[8] (machines from 30 kW upwards). Of course, we rely on manufacturers laboratory test results and labels/data sheets, which must be updated and accordingly done to the ISO measurement methodologies. In Table 3 the relationship is identified as $P_4 = f(q_4)$, or else $q_4 = g(P_4)$. Figures 5, 6, 7, 8 and 9 are placed at the bottom of the paper for the sake of reading and they report the power-capacity relationship for the commonest pressure levels in industry (0.4, 0.95 and 1.2 MPa for this latter only for P_4 < 100 kW).

Given (i) the pressure level, (ii) the average capacity over the time span (q_4) and (iii) the size of the machine, then the input electric average power is obtained from the suitable curve.

In Table 1 the list of data to be recorded and related instruments are described respectively for SP1 and SP2.

6. It means that the supplied power is measured upstream and it also includes auxiliary devices (i.e. fans,etc.).

7. FAD is defined according to ISO 1217(1996) standard.

8. These data come from the elaboration of technical information inferred by the datasheet of compressors, currently available on the market offered by the major manufacturers. These data have to be provided accordingly to the related ISO procedures. In the final remarks the authors propose to involve the manufacturer associations to be liable for the issuing of these data. Too many measures would affect the cost effectiveness of the procedure, nevertheless they are not excluded.

Table 1. Data to be recorded over the two sampling periods

time	CONFIGURATION	measurable variable	Measurement instruments or sources of information
SP1	baseline	power from the grid at LC[1]	Digital watt meter or equivalent instrumentation
SP1	baseline	power from the grid at NLC[2]	Digital watt meter or equivalent instrumentation
SP1	baseline	operating hours at LC	Onboard recording
SP1	baseline	L/NL cycles	Onboard recording
SP1	baseline	operating compressor pressure	pressure gauge
SP1	baseline	F.A.D[3]	Flux meter or technical data from measures taken according to ISO 1217 (1996) standard
SP2	VSD	Cumulative outlet air	Onboard recording[4] or flux meter
SP2	VSD	cumulative operating hours	Onboard recording
SP2	VSD	operating compresso r pressure	pressure gauge

1LC load conditions; 2 NLC no load conditions; 3 FAD free air delivery, according to ISO 1217(1996) definition; 4 The record is an internal assessment, deducted from the RPM of the machine. This relationship is legitimate for reciprocating/rotary compressors where there is a linear relationship between speed and quantity of compressed air delivered

Table 2. List of data from the SP1 campaign

Recorded or calculated variables on the old configuration, during SP1	Measured	Assessed	From technical data sheets
Supplied load power in the steady state (P_1, kW) - full package	X		
Supplied unload power in the steady state ($P_{2,0}$, kW) and P^1_2 - full package	X	X	X
Hours in the load-mode (A_1^1, h)	X		
Hours in the unload mode (A_2^1, h)	X		
Offline hours (A_3^1, h)		X	
Load/unload cycles (c^1)	X		
Outlet pressure level (p^1_{set} , MPa)	X		
Rated delivered air FAD (q_1 , l/min)			X

Table 3. List of data from the SP2 campaign

VSD Recorded variables, during SP2	Measure d	Instruments	measuring standards
Cumulative amount of compressed air over SP2 (Q^2)	X	on board reading or from a continuous measurement instrument	According with ISO 1217 (1996) m^3
operating hours on VSD (A_4^2)	X	on board reading	h
outlet pressure (p^2_{set})	X	machine settings or pressure gauge	MPa

PROPOSAL OF A SIMPLIFIED METHODOLOGY – THE MONITORING STAGE AND THE ENERGY SAVINGS ASSESSMENT

During the first recording period SP1, described in details in [Anglani, 2007], several variables are recorded or calculated, in order to account for the air requirements delivered by the baseline compressed air system, therefore for its energy consumption. Table 2 reports the list of those data: P_1^1, P_2^1, A_1^1, A_2^1, A_3^1, q_1, c^1, p^1_{set}.

The results of this procedure allowed to assess the potential energy savings, hence promoting the change towards the system configuration that is going to be monitored in the following. Once the replacement of load/unload compressor with the VSD machine has taken place, the second monitoring sampling period can be scheduled and the performances of VSD compared with those of the previous system (load/unload controlled compressor) through an *indirect*[9] comparison. During SP2 some data need to be recorded: (i) the amount of compressed air over the sample period (or the electricity consumption and technical data sheet of the compressor) and (ii) the operating hours (Table 3[10, 11]). The superscript 1 or 2 of the variables identifies when the measure is taken (either over SP1 or SP2). If no

9. Indirect means that for each sampling period only one compressor is monitored, while the performance of the concurrent one is inferred by the illustrated procedure.

10. Cumulative amount of compressed air over SP2 (Q^2):The basic idea is to come up with reliable assessments, starting from data already available on the machines (i.e. the different operating hours). This is the reason why we do not propose to continously record energy over SP1 or SP2, instead, we propose a "once for all" record of the power P_1 over SP1.

11. On board reading: The displayed value, often, is not a real flux measure, but it is inferred by elaborating data on RPM (revolution per minute), which is the truly monitored value. This evaluation is legitimate in rotating compressors, being proportional the relation amongst RPM, the delivered capacity and the supplied input power.

superscript is reported then the data do not change (they are not variant). These time-independent value are: P_1, $P_{2,0}$ and q_1.

Once SP2 has been defined and set equal to n^2_{tot} (one week, a quarter, etc., a significant time span) the required measurements are:

- the network pressure p^2_{set}
- A_4^2 the VSD operating hours over n^2_{tot};
- Q^2 the delivered air over n^2_{tot} at $p^2_{set.}$ Such data can either be read on-board or monitored by means of a flux meter.

The assumptions supporting the current comparison are: (i) the SP2 time span needs to be equal to or a multiple of SP1, (ii) the air, delivered by the two machines must be the same amount, at the same pressure ($p^2_{set}=p^1_{set}$)[12] and (iii) $A_6=A_3^2$ (same off-line hours for the two machines, n_{off}^2). Based on these premises, the outcomes will provide data on the actual electricity consumption of the VSD based compressor and allows to compare it with the calculated consumption of the old load/unload controlled machine, operated to deliver the same service.

If both n^2_{tot} and A_4^2 are known then

$$n_{off}^2 = A_6 = n_{tot}^2 - A_4^2 = A_3^2 \quad h \qquad [1]$$

accordingly q_4^2, representing the average capacity delivered by the VSD over A_4^2 to the network, is equal to:

$$q_4^2 = Q^2 / (A_4^2 \cdot f_1) \quad m^3/min \qquad [2]$$

being f_1 the time conversion coefficient from m^3/week (if SP2 lasts one week) to m^3/min.

Given the size of the machine, the average supplied input power P_4^2 for the VSD system is obtained by properly referring it to one of the proposed curves.

The consumption of energy over SP2 is thus:

$$E_2^2 = P_4^2 \cdot A_4^2 \quad kWh \qquad [3]$$

In order to correctly assess how much energy the old load/unload controlled machine would have consumed, for the same amount of air delivered to the end users by the VSD based system over SP2 (Q^2), a few adjustments of the previously recorded data over SP1 are needed. In the following the same variables listed in Table 2, will be reported together with the mentioned adjustments: the superscript "2" will be used for the sake of comparison.

New definitions of (i) hours in the load-mode (A_1^2, h), (ii) hours in the unload mode (A_2^2, h) and (iii) off line hours (A_3^2, h) are needed over SP2:

$$A_3^2 = n_{tot}^2 - (A_1^2 + A_2^2) \qquad [4]$$

where $A_1^2+A_2^2$ is the overall time when the load/unload controlled compressor would be fed (so called "on" status).

Besides, the operating conditions of the load/unload controlled compressor to match the new requirements can be different from those recorded over SP1; hence there is the need to adapt its operation as if it had delivered the new amount of air Q^2, instead of Q^1. As a matter of fact, it is likely that, even if SP1 and SP2 are identical, the end users demand of air can change over time.

With this intent, the following assessment is required:

$$A_1^2 = Q^2 / (q_1 \cdot f_1) \qquad [5]$$

A_1^2 represents the hours in the new simulated load mode, Q^2 is the delivered air over SP2 and q_1 is the rated delivered air (FAD, the not variant data).

Given n_{tot}^2, since both A_1^2 and A_3^2 are known from eq. [5] and eq. [1], then A_2^2 is calculated from eq. [4].

Now the value P_2^2(kW), representing the average unload input power (supplied power during the simulated unload mode, that is when the compressor is not operating but still it is fed by the grid) over A_2^2, is newly assessed as in the following:

$$P_2^2 = P_{2,0} \cdot (A_2^2 - t \cdot c^2) / A_2^2 + P_1 \cdot t \cdot c^2 / A_2^2 \qquad [6]$$

As discussed in [Anglani, 2007] the time parameter *t* depends on the type of compressor, (t = 5 s for lubricated machines, t = 15 s for not lubricated ones), while c^2, the duty cycle, which indicates how often the machine switches from load to unload mode, requires to be newly assessed (in the SP1 procedure it was a recorded data).

$$c^2 = c^1 \cdot Q^1 / Q^2 \qquad [7]$$

Finally, the simulated consumption of load/unload controlled compressor can be assessed:

$$E_1^2 = P_1 \cdot A_1^2 + P_2^2 \cdot A_2^2 \quad kWh \qquad [8]$$

The energy savings over SP2 by the VSD monitored configuration can now be calculated as the difference between eq. [3] and eq. [8]:

$$dE = E_1^2 - E_2^2 \quad kWh \qquad [9]$$

The assessment of the gross energy saving (primary energy saving) over one year depends on the national efficiency of the electricity production. In particular for Italy this value has been recently set to 0.187 . 10^3 toe/kWh [AEEG, 2008].

$$GES = dE \cdot 0.187 \cdot 10^{-3} \cdot N \quad toe/y \qquad [10]$$

If SP2 is one typical working week then N represents the number of equivalent working weeks in one year; if SP2 is a quarter of a year, or a different period, N has to be properly calculated.

WH (yearly working hours) =
N (time span/year)· n_{tot}^2 (h/time span) [11]

In Table 4 the whole procedure is summed up.

12. If the pressure level is different then some further adjustment are required. The linearization tool can be used amongst pressures.

Table 4. Summarizing table of the monitoring procedure over SP2 (bold values are the known variables)

VSD installation					Load/unload controlled installation			
	Unit meas.	On line mode	Off line mode	Total	Load mode	Unload mode	Off line mode	Total
hours	h/ sett.	$\mathbf{A_4^2}$	$A_6 = n_{tot}^2 - A_4^2$	$\mathbf{n_{tot}^2}$	$A_1^2 = Q^2/q_1 \cdot f_1$	$A_2^2 = -A_1^2 - A_3^2 + n_{tot}^2$	$A_3^2 = A_6$	$\mathbf{n_{tot}^2}$
Delivered Air	m^3/ sett.	$q_4^2 = Q^2/A_4^2 \cdot f_1$	0	$\mathbf{Q^2}$	$\mathbf{q_1}$	0	0	$\mathbf{Q^2}$
Supplied input power	kW	$P_4^2 = f(q_4^2)$	NS	NS	$\mathbf{P_1}$	$P_2^2 = \mathbf{P_{2,0}} \cdot (A_2^2 - t \cdot c^2)/A_2^2 + P_1 \cdot t \cdot c^2/A_2^2$	$P_3 = 0$	NS
Energy consump.	kWh/ sett.	$P_4^2 \cdot A_4^2$		$E_2^2 = P_4^2 \cdot A_4^2$	$P_1 \cdot A_1^2$	$P_2^2 \cdot A_2^2$	$P_3 \cdot A_3^2$	$E_1^2 = P_1 \cdot A_1^2 + P_3 \cdot A_3^2$
Gross energy saving	Toe/y	$GES = (E_1^2 - E_2^2) \cdot 0.187 \cdot 10^{-3} .N$						

Table 5. Needed data for the final assessment

Measured data over SP2 – VSD37 AC	Unit measure	Value
Network pressure level	MPa_r	0.7
n_{tot}^2	h	168
Q^2	m^3/week	16 828
A_4^2	h	160
Other known parameters from the previous monitoring stage SP1 on the old GA37 machine		
C		12,600
q_1(FAD)	m^3/min (l/s)	7 (115)
P_1	kW	47.9
$P_{2,0}$	kW	13.2
Q^1	m^3/week	14 697 (assessed)

Table 6. List of calculated parameters

Variables	Equation number/curve	Unit measure	quantity
n_{off}^2	eq. [1]	h	8
q_4^2	eq. [2]	m^3/min	1.75
P_4^2	from the graph [fig.3]	kW	15.7
E_2^2	eq. [3]	kWh/week	2 511

The case study. Application of the procedure to a mechanical company

The validation of the methodology has been applied to several case studies: in the following the case of a company of the mechanical sector (equivalent to the NAICS 3335 sector) is considered. The feasibility proved that the change from a load/unload controlled compressor to a VSD machine would be profitable from an energy standpoint.

An Atlas Copco GA37 lubricated compressor was operated over SP1: in case of a replacement with a VSD machine, over 42 working weeks/y, the provisional gross energy saving was assessed equal to 21,25 toe/y.

Once the replacement has taken place (the new lubricated machine is a VSD37 AC which is a system including the same compressor as the GA37 and an asynchronous motor driven by an inverter) the monitoring procedure has been organized: SP2

Table 7. Simulating the load/unload controlled compressor functioning: updated values over SP2

Variables	Equation number/curve	Unit measure	quantity
A_1^2	eq. [5]	h	41
A_3^2	eq. [1]	m3/min	8
A_2^2	eq.[4]	kW	119.4
t		s	15
c^2	eq.[7]		12 600
P_2^2	eq.[6]	kW	30.7
E_1^2	eq.[8]		5 608

Table 8. Final results of the comparison

			VSD CONFIGURATION			SIMULATION OF THE GA37 COMPRESSOR			
			On line mode	Off line	Total 1	Load mode	Unload mode	Off line	Total 2
hours	(A)	h/w	160,0	8,0	168,0	41	119,4	8,0	168,0
Delivered air (FAD)	(Q)	m3/w	1,75	-	16.828	6,9	-	-	16.828
Supplied input power	(P)	kW	15,7	-		47,9	30,7	-	
Energy consumption	(E)	kWh/w	2.511	-	2.511	1.947	3.661	-	5.608
GES/week						0,5792			

has been chosen equal to one typical working week and the following data have been recorded on the new machine while few others are taken from the old configuration in order to assess how the old system would consume under these new operating conditions (Table 5).

According to the procedure, for the VSD machine the data are assessed (in Table 6).

Next, the comparison with the old machine has to be performed, assuming that now the whole air delivered over the week is equal to Q^2. In Table 7 the simulated parameters are reported.

Once these data are set in the summarizing Table 8 (assessment of Table 4), then both dE of eq.[9] and GES of eq.[10] can be defined.

From the illustrated procedure the gross energy saving over the sample period has thus been assessed.

Remarks on the methodology

A few aspects of the procedure deserve to be clarified. First, there is a difference between the *a priori* saving evaluation (based on SP1 monitoring) and the assessment carried out over SP2 after the replacement of the old machine. Indeed, it is very unlikely that the same identical operating conditions occur during two subsequent sampling periods. Air demand is a very time dependant variable and even though a process could be quite standardized in its requirements, still some differences have to be accounted for. This is why the two procedures over the two sampling periods need to be harmonized in the handling of data. The novelty of the illustrated methodology lies in relying on few and cheap measurable data and references curves: the duty cycle "c" of the load/unload controlled machine, the operating hours and the overall air delivery of the VSD compressor. The choice of taking into consideration the "on board data" allows to minimize verification costs, thus keeping under control those costs related with measurement tools and personnel.

Between the two sampling periods conditions can change, thus the two assessed values of energy saving (the GES) can be different, hence the second issue deals with the choice to make over the correct value. One fundamental consideration is that the more the load/unload controlled compressor operates in an unload mode, the more convenient the replacement with a VSD is. While working with no load, a compressor is still consuming energy (20-25% of the rated power) without delivering any service; thus it is an unsafe practice to make any assessment, without taking into a proper account the "on board data", namely those data directly measured and displayed on the machine, which depend on the operating conditions of the machine. This is one bright side of the bottom up methodologies.

To prevent any overestimation of savings, the minimum between the two calculated values can be taken into consideration and this position could also satisfy the *additionality* question. Nevertheless the accuracy of the methodology should come first and the authors would very much stress the need of a careful debate on that. The proposed universal curves have already been elaborated by carefully weighting data from several manufacturers: anyway there is also the possibility in the stage of a M&V procedure for a customer to supply the real technical data measured on the machine. The graphs we propose should be updated every 3-5 years since the market offers new technological solutions with improved performances: our proposal can be strengthen by having these data coming from the compressor manufacturers European or International association which could be involved by being liable for the issuing of such curves. Besides, the proposed methodology only accounts for the optimization of the single device (the generation of compressed air), leaving aside the whole system optimization, which has to be performed in advance to any change [Radgen, 2007][Oberschmidt, 2007].

Just to give an idea of the involved market for Italy: in 2007 the mechanical sector consumed roughly 3,6 TWh/y (less than 10% of the national electricity consumption). As a rule of thumb, a share between 5 and 10% of electricity is accounted for the compression of air in the sector (180-360 GWh/y): a potential underestimated saving of energy between 15-25% for the sector can determine a benefit of 27-90 GWh/y (13.5-45 $ktCO_{2eq}$/y emissions reduction), that is the equivalent production of a 6 MW_e power plant.

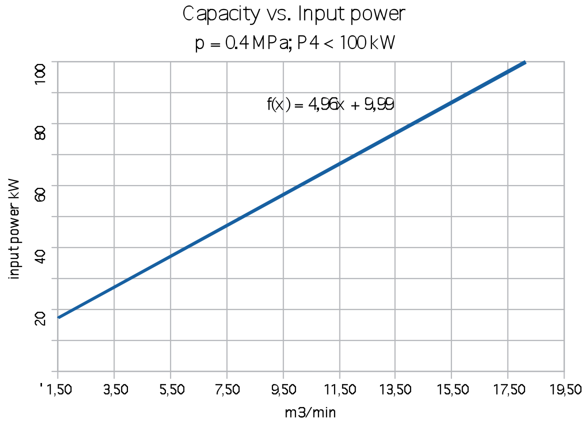


Figure 5 Proposed universal curve, relating capacity and supplied electric power (p_{set}=0.4 MPa, P_4 < 100 kW)

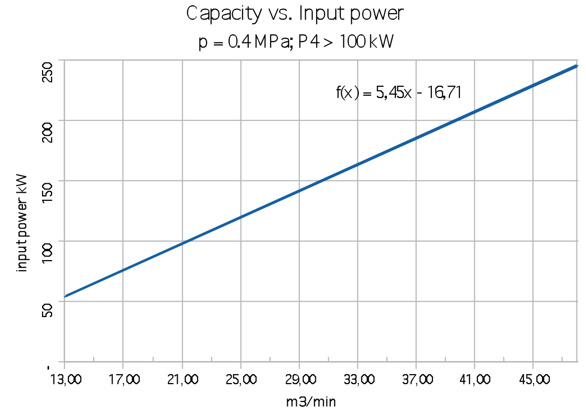


Figure 6 Proposed universal curve, relating capacity and supplied electric power (p_{set}=0.4 MPa, P > 100 kW)

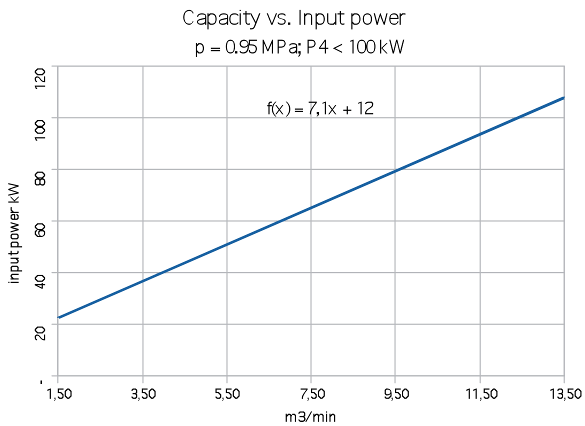


Figure 7. Proposed universal curve, relating capacity and supplied electric power (p_{set}=0.95 MPa, P_4 < 100 kW)

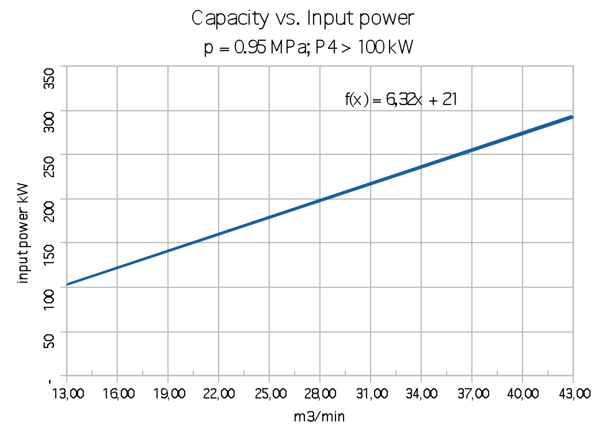


Figure 8. Proposed universal curve, relating capacity and supplied electric power (p_{set}=0.95 MPa, P_4 > 100 kW)

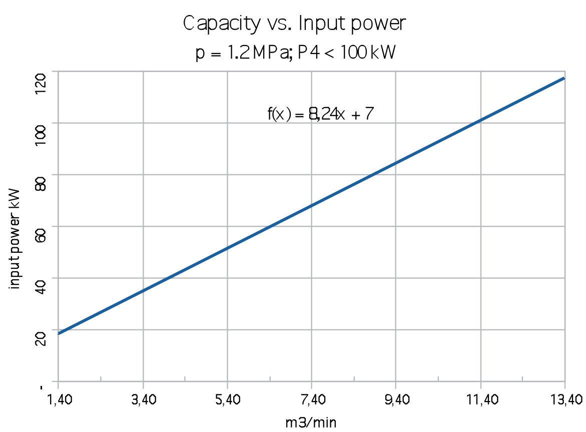


Figure 9. Proposed universal curve, relating capacity and supplied electric power (p_{set}=1.2 MPa, P_4 < 100 kW)

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Endnotes

The methodology has been elaborated for and submitted to the Italian Regulatory Authority for energy and gas (AEEG). The procedure is currently under evaluation.