Compressed air systems: factors affecting the adoption of measures for improved efficiency

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Abstract
The sustainability and competitiveness of industrial activities may strongly rely on increased energy efficiency. In that, compressed air could be one of the most expensive forms of energy in industry because of its low efficiency. Nonetheless, compressed air is widely used, and is considered as relevant in many facilities, accounting for even more than ten per cent of industrial electricity consumption in the EU, in US and in China. Moreover, it should be noted that the life-cycle cost of a compressed air system is mostly covered by the operating costs, so that most of the measures to lower energy consumption pay for themselves almost immediately, producing relevant monetary savings. Nevertheless, several studies show that the adoption rate of such Energy Efficiency Measures (EEMs) is still low. For this reason, we have carefully reviewed scientific and industrial literature over EEMs for Compressed Air Systems (CAS), so to get useful insights into the main factors leading to their adoption. Our study lays a good foundation for a novel framework aimed at describing and characterising EEMs in CAS, revealing that, so far scientific and industrial literature has mostly presented energy and economic factors, thus giving little room to other factors that still could be quite relevant for an effective EEM adoption, such as compatibility of the measure within the production system (e.g., adaptability to different conditions, presence of different pressure loads), complexity of the production system (e.g., accessibility for operational activities, expertise required for implementation), observability of the performance (e.g., impact on air quality and/or safety). The framework could result in a valuable tool offering different perspectives in the decision-making of industrial managers and technology suppliers, as well as industrial policy-makers.

Introduction
The relevance of industrial energy efficiency is due to several factors. First of all, the global trend of energy consumption is going to increase by 49 % in the horizon 2011–2035, and a primary role can be attributed to the huge growing trends of non-OECD countries (1). Secondly, among the four main sectors (transport, industry, residential and services) in IEA countries, the highest share of energy consumption (more than 30 %) is attributable to industry. Heterogeneity of industrial sectors is a key factor to be taken into account when thinking about solutions for the diffusion of Energy Efficiency Measures (EEMs). Especially in small and medium-sized enterprises (SMEs), the lack of standard procedures as well as internal competences for a sound decision-making process can represent too high barriers, as previous research has shown (2), (3), (4). The industrial sector in Italy is highly diversified and the presence of SMEs is spread all along the Peninsula, whose number exceeds the 99 % of the total, employing more of two thirds of the industrial workers. The heterogeneity of industrial activity leads to a wide spectrum of potential sources of energy efficiency: indeed, companies could either implement sector-specific EEMs or adopt EEMs within cross-cutting technologies. As evidenced by previous research (5), (6) whereas broad efforts have been so far paid towards sector-specific EEMs, little attention has been

devoted to cross-cutting technologies, for which one may find the greatest potential for energy savings.

Among others, the Compressed Air System (CAS) has revealed to be one with strong interest. Indeed, the compressed air, known as the *fourth utility*, have other some characteristics that may explain the low adoption rate but others that may render it attractive for efficiency outcomes. First, it is used mainly as a service. Second, it is not a productive output. And, third, it is really widespread within all production industries (7). According to Radgen and Blaustein (8), energy saving interventions are considered as more convenient with respect to other industrial investments, but compressed air related measures have low rates of adoption for organizational and cultural reasons.

In a nutshell, despite compressed air is usually overlooked, not being part of the production process, improving its energy efficiency on the one hand may lead to relevant savings, on the other it may have a positive influence over other sources of energy consumption (and potential efficiency). For this reason, it is really important, starting from an analysis of singular EEMs in CAS, to get a better understanding on the main factors to take into account when undertaking a decision of adopting them. In the following, we have tried to give a contribution in this direction, by analysing CAS as well as their main EEMs. We conclude our study with some remarks for a comprehensive framework to be adopted by industrial decision-makers as well as policy-makers to understand the main factors leading to the adoption (or not) of EEMs about CAS.

Compressed Air Systems: a short technology overview

As air is available and can be easily supplied, it is usually treated as cost-free. Despite this belief, usually a non-negligible portion of energy costs in an industrial environment comes from the CAS. This widespread misconception about inexpensiveness, most of times is translated to a poor focus on the efficiency practices and on the optimization of compressed air, i.e. energy savings potentials are seldom considered in the design phase. The widespread diffusion of the technology is brought by a series of factors: the ease of handling, the great safety, being sometimes preferred to hazardous environments for their low flammability, and the relative ease of maintenance procedures. As indicated from data available in industry facilities (9), such systems should be used only if there are some additional benefits, such as safety enhancements, productivity gains or reduction of labour due to high energy delivery cost. But, in order to fully understand the main factors leading to the adoption of EEMs, it is important to understand the technical and operating features of CAS. For this reason, due to the illustrative nature, most of the following in the present section – with a description of CAS by main components – is taken from relevant industrial literature sources (10), (11).

GENERATION OF COMPRESSED AIR

Compressors are the principal components of the system. Two different types of fluid compressors exist: dynamic and positive displacement. Dynamic compressors are divided into: axial, when the air passes through a series of rotating vanes, the hardware characteristics are compactness and lightweight, and which own high rotational speed and a compression ratio up to 16/18; centrifugal when air is accelerated by stages of impellors, with more stages which own very high rotational speeds (up to 100,000 rpm) and a compression ratio difficultly higher than three for a single stage, for efficiency purposes. Positive displacement compressors are divided into: reciprocating, vane, and screw compressors, the most used in industrial context. Regarding the screw ones, depending on the requirements of the final use in terms of air purity, this type of compressor is available as lubricated or oil free type. The differences in the two types of screw compressors lie in the possibility, with the *lubricant*, of sealing the compression chamber; moreover, this acts as a heat sink to cool the flowing fluid.

CONTROL AND REGULATION MODES

Air requirements are quite variable during the time and for this reason, there is the necessity to operate not always at full load, in order to vary compressed air production depending on needs. The efficiency of the system is determined on the quantity of air saved when not needed and on the promptness of changing of load over time i.e. an efficient of flow control at part-load is required. Depending on the system took in place and on the control selection, the overall system performance can be deeply affected, and the energy efficiency as direct consequence. The strategies for the flow control are plenty, depending on the compressor type, acceptable pressure variations, air consumption variation and acceptable energy losses. The most common types of control are as follows: (i) Start/Stop; (ii) Online/offline; (iii) Modulating control; (iv) Inlet guide vanes; (v) Variable displacement and (vi) Variable Speed Drives (VSD).

AIR TREATMENT UNITS

Dryers. Downstream the compressor, the air is normally at higher temperature with respect to the ambient, and the aftercooler gives a very high relative humidity. To avoid the moisture entering in distribution pipes, the drying units are the minimum requirement for every CAS. The temperature and the degree of humidity of air depend on operating conditions, as consequence different dryers have different characteristics. For instance, operating in a very cold environment, we need the dew point of air being lower than the ambient conditions to avoid any ice formation. Three different types of dryers exist, namely refrigerant, desiccant and absorption. *Filters* can be placed before the compression units, to shield from airborne atmospheric particles and other impurities, or downstream the compressor to drop out the excess lubricant in units that include it. Both types should be changed periodically, but the former is much easier to replace. *Heat reduction units.* Cooler units can be placed at the intake of the compressor, between stages or immediately before the dryers. Intercooling effects have the same of the intake compressor position since they place before the next step of compression; the place of the intake cooler lowers the air temperature (T) entering the compressor, increasing the efficiency, since the air density is higher at lower T, permitting more air entering the compressor for each rotation of the rotor.

ANCILLARY EQUIPMENT: RECEIVERS AND SEPARATORS

A capacity storage is required for maintaining the system stability over time, but also to maintain the required efficiency and the highest possible quality of air. Here a classification is operated between the primary or secondary type, depending on the task performed. The former, acts as a general system storage of air, and its location is close to the main compressor in case of multiple compressors layout, but the exact location depends on the need of either upstream or downstream cleaning-up equipment; it is used to supply peak demands, reduce cycle frequency of screw compressors or to damp pulsations for reciprocating units. The secondary instead are located in the distribution system of the facility or at the end use points, having the protection task for pressure dips or large transient users. Moreover, it can supply the adequate stability wherever the piping is undersized for the current demand. Separators have the task of separating liquids within the air. They should be installed after each intercooler.

DISTRIBUTION NETWORK

Distribution network has a strategic importance in a CAS. It gives to the air the possibility of moving from the generation point, to the point where one should use it. The distribution system is composed at most, by piping. The piping is connected with others by mean of fittings for the directional changes or to cope for the length of the entire line. The network path, design and sizing are important for multiple reasons: system efficiency, reliability and production costs.

POINT-OF-USE EQUIPMENT

It can be actuators that are in charge of performing mechanical work owing to the linear displacement or rotation of elements; they use energy that is given by the compressed air and operate the transformation in mechanical energy. Some application of actuators is found in the air-driven vane motors. Summarizing, the compressed air is used in a very huge number of ways within the industrial context; USDOE (11) specifies that the electric-driven units' counterpart of pneumatic tools, are much more convenient to use from an energetic viewpoint. Compressed air usage is thus suggested only when strictly required.

Analysing Energy Efficiency Measures in CAS: an overview

ENERGY EFFICIENCY MEASURES IN CAS

EEMs are defined as "technologies or behavioural changes that reduce the specific energy consumption of a particular process" (12). The direct consequence is the optimization of heat and power consumption, to gain greater energy-driven productivity. The benefits coming from their adoption are of different nature: the reduced energy bills are source of tangible revenues, but further benefits are also greater capacity utilization, reduced scrap rates, more effective emissions and safety compliance, and enhanced risk management (13). The industrial contest is so various, that energy management practices are highly situational; in SMEs decisions about energy efficiency investments are usually in charge of the facility manager, especially when the energy manager is not present (the presence of the energy manager is instead compulsory in Large Enterprises).

The reason why the importance of investment opportunities in EEMs in compressed air systems should not be underestimated is its high operating costs that can overcome the 70 % of the total lifecycle costs (10). But, it should be also noted that compressed air should be always treated as a system. Indeed, single components assessment is never suggested by industrial literature manuals (11), and the system approach is revealed to be the way to handle inefficiencies. Here the main steps to consider when improving energy efficiency in CAS (11): (i) Establishment of the current conditions and operating parameters; (ii) Determination of present and future production processes need; (iii) Gather and analyse operative data, developing the load duty cycles; (iv) Analysis of alternative system design and improvements; (v) Determination of the best opportunities, both technical and economical; (vi) Implementation of the more suitable options; (vii) Analysis of operations and energy consumption and validation of performances; (viii) Monitor and optimize the system; (ix) Operate and maintain the system to peak performances. This guideline represents the ideal practices to be followed for the elimination of whatsoever inefficiency, but some common procedures for specific hardware or operations should be analysed individually. Moreover, the different sets of technologies and operative solutions to lower inefficiencies of this system is so large, that the characteristics of each of the most recommended EEMs should be pointed out, to investigate deeply the possibility of higher savings, and to start understanding what are the major causes of the low adoption rates of some of them.

OVERVIEW OF MAIN EEMS IN CAS

A very useful instrument for the analysis of the single efficiency measures has been developed by the US Department of Energy, with the Industrial Technology Program (acronyms ITP), related to energy management topics. In fact, the recommendations cover also other types of interventions as the waste minimization (or pollution prevention) and direct productivity enhancements, that nevertheless do not fall within the scope of the present study. All the main recommendations of EEMs are grouped together from the assessments performed by the Industrial Assessment Center (IAC) centres (14), which consist in in-depth evaluations of EEMs opportunities in facilities. After the remote survey of the plant, a detailed process analysis to generate specific recommendations for different types of systems follows. CAS interventions are categorized with the first digit referring to energy management practices (digit 2), the second specifies the prime mover (in our case motor systems, digit 4), the third is the air compressors specification (digit 2) and then, the last one refers to hardware or operations related interventions. For a matter of completeness, we add also other EEMs that does not influence the performances of CAS, but that highly depends on CAS status: they are thermal system related, more precisely about heat recovery from specific CAS equipment (2,243X).

EEM 2,4221: Install compressor air intakes in coolest location

The intervention is based on the installation of the compressor inlet in a cool location for the thermodynamic benefits offered by new air conditions. The air can be aspired from the external environment, or from an indoor area. The lower the inlet temperature, the more air can enter the compression unit. The cooler the air, the denser is, increasing the mass flow and pressure capability.

Operations and technology. Technology experts (15) and experimental investigation (16) showed that the typology of compressors and individual controls have a huge impact on the performances. Moreover, if the new location is very difficult to access (roof or difficult location accessibility in winter months, etc.), the difficulty maintenance procedures may have a huge impact on the effective energetic gains of the EEM, even more than the difficult prediction of the ambient conditions. Aspirating air from an internal ambient can entail a pressure reduction under the atmospheric conditions, leading to lower compressor efficiency because the reduction in static pressure influences the compressor ratio (17). This risk is prevented thanks to ventilation also contributing to reduce the inlet temperature. The installation in an external shaded area can be responsible of up to 10 % power consumption savings in summer months (18). This installation generally requires higher engineering processes, owing to the necessity of monitoring the average ambient air condition in real time.

EEM 2,4224 Upgrade controls on compressors

As seen above, the baselining of control measures has a crucial role in ensuring efficient system operations as well as high performances, with the purpose of lower input power. This intervention is one of the highly dependent on the other CAS equipment operating conditions and one of the most expensive, but this ensures high savings potential. Both for singular and system controls, the system operations are addressed through: (i) delivering of sufficient variable flow to achieve stable pressure at the end-use point; (ii) efficient working conditions, to ensure the lowest energy consumption; (iii) tracking and transmit information about current operative data. The control methods to apply on compressors are useful to: (i) match the supplied compressed air to meet the demand; (ii) supplying the right power; and (iii) ensuring that the minimum required pressure is maintained for the proper working of all end-use equipment.

Operations and technology. To ensure a continuous service, the controls application to each single compressor is highly recommended; eventual backup units prevent unplanned downtime. Despite on the one hand proper control applications help a lot for efficiency and other benefits, on the other, bad applications lead to higher costs and increased maintenance. VSD application on rotary screw compressor is at constant torque load. When the retrofit in rotary screw and reciprocating compressors is performed, one may ensure that correct levels of lubrications are maintained, vibration problems are avoided, and cooling is enough. Centrifugal machines characteristics prescribe an optimal running speed, so this installation is not suggested. Smart *central system control* can manage multiple compressors of different sizes, allowing the reduction of energy consumption in different ways. The cost of a central control system depends on the intelligence of the system and on the number of compressors that can be managed, on the installation cost and on the capability to be integrated in plant process control system (19–20).

EEM 2,4226 Use or purchase optimum sized compressors

This EEM refers to the purchase of a compressor able to follow and handle the demand of the system in any time with efficient operation. Oversizing or installing a wrong number of units are two of the major problems in the supply side of CAS. The compressor working conditions highly influence other equipment; the installation of a new compressor in a pre-existent system can change the way the system performs. The general rule when substituting a compressor unit is to look for the specific efficiency, in kW/100 cfm, for ranges of capacities (from full load to fractions of it) and see the suitable unit, considering dimensions, ease of handling, monitoring and maintenance requirements.

Operations and technology. For the installation of an optimum sized compressor, operating conditions in terms of capacity, pressure and temperature should be checked. Here some important considerations follow, to be evaluated when designing a new system (21): (i) Pressure: inlet P should not go under a minimum; moreover, the inlet filtration and losses in inlet hood and piping should be considered to guarantee performances; (ii) Temperature: for inlet T influences, refer to EEM 2,4221; the discharge T is affected by inlet T, P, and compression efficiency, which is quite important to be monitored for determining the design of more stages (intercooled).

EEM 2,4231 Reduce the pressure of compressed air to the minimum required

The pressure is the major parameter for delivering air at optimal conditions. In any case, the pressure of the system is set on the minimum for the requirements by end-users. Starting from the point of use one can go backwards, identifying losses and determining what is the supply pressure required. The good design of the system should prescribe losses lower than 10 % (without pressure reducers) (22) (11) from the production to the delivery of compressed air. Other than compressors, most of components have an influence on the pressure: piping, valves, dryers and filters. As a rule of thumb by many manufacturers and technicians, for every 0.138 bar increase in the discharge pressure, the energy required by the compressor goes up by 1 %.

Operations and technology. Distribution, demand side and CAS equipment, are possible sources of pressure drops. The pressure reduction gives additional benefits as the reduction of the total flow (23); in some cases, this can lead to lower number of compressors to run. Since the pressure losses can be located anywhere throughout the system, and most of the equipment change their performances working to a different pressure level, the measure is not independent from the system components' performances. Solution and benefits are the following:

- Correctly size the line for a maximum drop of 1–2 % and consider impact of future expansions on pressure reduction;
- A sound air treatment equipment should reduce corrosive fluid parts, that increase the pipes wearing, with a direct effect on pressure drops;
- In order to have a higher pressure at the end-use side, the choice to increase the pressure generated by the compressor is the worst from an economical viewpoint. It is not sure at all that this action leads to higher pressure at the demand side: losses and leaks are amplified by higher pressure and the demand side could be not see the consequences of the higher supply side pressure (10) (24);
- The utilization of modern regulation equipment can reduce the drop up to 0.5 bar;

- Specify size of components on actual flow rate and not average flow rate;
- Predefined pressure gauges are located downstream the compressor discharge;
- Check from components manufactures real pressure requirements;
- Consider the possibility of installing different compressors for low flow-rates high-pressure applications, rather than increasing the overall pressure of the system;
- Air receiver can act as shields, separating the compressor discharge from the distribution side. The control of system pressure downstream the air receiver can affect as much as 10 % of energy consumption.

EEM 2,4232 Reduce or eliminate the compressed air used for cooling, agitating liquids, moving products or drying

This EEM pertains the wrong use of the technology (i.e. compressed air) that can be substituted by much more efficient equipment units. The alternatives are a lot, and cover a wide range of applications. The lack of knowledge diffusion in the adoption of new technologies is one of the major factors that can inhibit this type of investment.

Operations and technology. The technologies to use in place of compressed air are very different. Technologies can be replaced with new ones, much more energy efficient; the most relevant (in terms of variability of end-uses) are grouped here. An alternative in compressed air is found to be the *blower* technology, basically providing very low pressures with a high volume of air being compressed. The installation procedure is considered by blower suppliers as very easy in case of integration with existing compressed air network. In general, blowers are required when operating pressures does not overcome 2 bars (a typical use as substitution is found in the dense-phase transport air) and when requirements of air are constant in time. The *vacuum generators* are another typical inefficient use of the compressed air; the CA application is very easy to implement, the size is quite small, is lightweight, with no electricity required in the end-use point. Its low capital cost and promptness of availability (25) may render this application attractive. Moreover, if they have load coefficient lower than 0.3, their operative cost is lower than a centralized system. In all other cases, except for uses in a very wide area or for safety reasons, the compressed air applications for vacuum generation present high operating costs. The motor-driven dedicated vacuum pump is a valid alternative for the low dimensions and ease of installation, but the central unit has the disadvantage of a high initial cost as well as the design of the system. Two conditions for which use of vacuum generators (11) (compressed air driven) could be convenient are either low duty cycle (high peak load applications), or different vacuum levels required. Concerning to *blow-off* applications (26–27), the latest innovation in new technologies can be exploited, but always subject to cost competitiveness. In bottles industry, a good low-cost option is found to be the blending of compressed air with ambient air associated with high performance nozzles (Venturi type or engineered nozzles), for which the volume of air requirement is strongly reduced. This option can be a low-cost alternative to the more expensive passage to blowers, although of course not that effective from an energetic perspective. *Electrical fans* are a valid alternative for aerating areas where low power is required, but a constant air movement is needed. Is the most implemented solution for personal cooling substitution. The start-up phase is of utmost importance and inspections are user's responsibility, so that high technology knowledge is required. *Diaphragm pumps* suffer from the lack of specific equipment for their control and regulation. The over regulation, with a pressure higher than necessary, leads to an increase of demand of compressed air; the other problem of this device is the amount of flow to provide, since it should be brought to the minimum required. *Pneumatic actuators* are used for their safety and precision characteristics, but many times the lower energy consumption of the electric actuators is to be considered as an alternative that has not to be underestimated. For many of the installations, the electrical service closeness from the point-of-use can hinder adoption of electric-driven technologies substitution.

EEM 2,4236 Eliminate leaks in inert gas and compressed air lines/valves

Leaks are the major source for cost savings in a CAS. The leakage of a small hole in the system can have a high impact on the final consumption, depending on the leak size and the pressure. Additional indirect drawbacks are present, such as the lower pressure by the system due to leaks that for long time can lead to malfunctioning of compressors' controls (that adapt their load to the new pressure established). The pressure drop, of course, determines an artificial demand (i.e. the higher flow rate required to working at a higher-than-required pressure) making the equipment run for more time than required, or at a higher pressure, in both cases leading to a lower lifetime (11). Leaks can be prevented by different operational good practices such as: avoid the wrong tightening of assembling parts, the incorrect handling of the components, the wear of the components and stressful operating condition for wrong material in place (28). *Leak management programs* have been developed along the years and implies seeking, repairing and the follow-up adjusting of equipment to increase compressors efficiency and overall CAS reliability. Although the key elements of the procedure are always the same, the potential of a leak repair program is very dependent on the correct baseline of the actual compressed air usage and on the real potential for savings through the calculation of leaks/pressure in place. A good leak management program (proactive detection and repair) ensures that leaks do not overcome 5–10 % of the total compressed air production. Inexperienced personnel tend to overestimate leaks volume, leading to potential savings that will never be reached. The passages for a sound leak management projects are: (i) Baselining the current state of the system; (ii) Estimation of leaks all along the site; (iii) Leaks detection; (iv) Leak documentation: to have a log about location, size for the prioritization of repair areas/specific leaks and also to act as feedback for future projects; (v) Once the major/all problems are fixed a post-project is fundamental for the efficient operation in new system conditions i.e. regulating again the controls on single compressors and setting the new pressure range in the mains as the operational ones.

EEMs 2,2434- 2,2435 Heat recovery from air compressor and other equipment

The amount of heat that can be recovered in CAS can be really huge, and therefore is a great opportunity to be exploited in some cases. The recoverable heat flux is distributed across several areas: referring to screw compressors, 5% remains in the drive motor, whilst 75 % can be recovered to the fluid cooler units, and the remaining part by the after-cooler.

Operations and technology. Heat recovery opportunities in different screw compressors are different, with the water-cooled lubricant-injected compressor supplying hot water at around 70 °C. Air cooled fluid-injected have a lower thermal capacity, but the temperature range is similar. Water cooled oil-free units supply higher T water in the range of 90 °C, entailing much more opportunities for heat recovery. Built-in solutions for recovery can be present from the manufacturers of packaged compressors for recovery on this compressor type. The heat recovery process is highly influenced by the part load working of compressor, so that the trim units have much lower amount of heat recoverable that is lower with the increase of part load working time. A good planning (29) (11) prescribes the data collection to estimate the potential, before the installation, gathering above all: the fluid medium thermal capacity, temperature levels and differentials, volume flow rates, specific heat capacity of the media, hours of operations, continuity of the heat source and structural conditions. As the second step, the heat recovered can be used for many purposes, but careful attention should be paid before installation, to look for the right application in each context. The most common opportunities for heat recovery are: (i) Industrial process heating; (ii) Preheating boiling water; (iii) Make-up air heating; (iv) space heating; (v) Heat-driven chillers; and (vi) Heating food and beverage products. The thermal match between the produced hot air/water and the one required in the plant and the time match i.e. hours in which the compressor is running preferably at full load, with the required hours of hot stream are of fundamental importance. As authors note (30), the sensible difference in the time recovery of the investment depending on the final utilization has to be considered. Therefore, the decision-making process when considering heat recovery should take into account those considerations. In the following, a synthesis of some procedures and routines to check before to undertake the investment, highlighting the factors that influence barriers for the EEM is presented (31):

- Little knowledge in thermodynamics can lower the efficiency of the compressor where hot air recovered is taken from the compressor room and ducted outside (the direct consequence is the under pressure of the inlet ambient, that acts like a throttled inlet of the compressor);
- Maintenance efforts are increased because of the new equipment requirements;
- Identify opportunity for savings is not that easy since are needed both a thermal match (enthalpy levels) and a time match, so that the heat availability does not necessarily correspond to a profitable saving (17);
- Modification to existing equipment could represent hidden costs, accrued during the service life. Moreover, the tight monitoring of temperature, has a positive effect on compressed air equipment life (32);
- Air quality and equipment service life can be thoroughly influenced by a specific choice of both aftercooler as well as heat exchanger (32);
- For potential investment expenses, consider also the working hours per year of compressors, installed electrical power, compressor room location, local temperature range.

Towards a new framework for characterization of interventions in CAS

IMPORTANCE OF THE DECISION-MAKING PROCESS

The decision-making process starts with the recommended EEMs' analysis and ends with the implementation (or not) of the measure. The decision is not straightforward and may require a set of specific skills. Capability of forecasting future energy prices, technology developments, adapting the recommended technology to the current system and organizing the economical and labour resources properly are some of the required skills to consider for a sound decision. Moreover, the subjectivity naturally embedded by decision-maker can influence the weight of each element deemed as relevant. Nevertheless, in many cases (especially when dealing with SMEs) a single person takes decisions, leading to unavoidable problems. In fact, as highlighted by previous research (33), the decision-maker is bounded in its decision by many limitations and attention on resources because of the human capability of dealing only with a limited set of information. For this reason, based on the system and firm conditions, one may pay attention to some problems only and tend to hide some other aspects, creating an underestimation or overestimation of achievable savings. For this reason, in order to fully support industrial decision-makers, a comprehensive framework, able to help the EEMs adoption decision about the specific technology of CAS is needed. To start, it is really crucial to sketch the main characteristics of the single EEMs. The values assumed from each attribute, i.e. factor, can be known with reasonable certainty or not, depending on the EEM and how it adapts to working conditions. But, what is of utmost importance is the perspective through which analysing the EEMs and related factors. By considering that different user typologies entail different adoption strategies, so that the perspective can result as different (according to being, e.g., either private or industrial final end users, or policy makers), since we are interested in industrial decision-makers, the perspective of the work has to be set accordingly. For the industrial end-user, each energy efficiency investment is translated into monetary terms, and the availability of implementations in terms of cost and opportunities has to be approved by the top management.

LITERATURE BACKGROUND ON FACTORS DESCRIBING EEMS

The characteristics of EEMs are often regarded as neglected dimension (33–34), and this has revealed to be particularly true for the cross-cutting technologies (6) (4), where often the lack of strategic value hinders the interest towards the argument. As presented above, the role of compressed air is indeed underestimated and the operative costs are the major share of the lifecycle costs, in some cases even more than 70 % (9). Many authors provide information on additional features of EEMs with the development of different list of characteristics or the built of framework to address the features that come from the adoption of an EEM in different contexts. Previous research (35) focused on the enhancements with respect to operating condition such as: increased productivity, capacity utilization, reliability or quality of the product, reduced production or environmental compliance costs, but do not give a rationale behind their choice. They pointed out the productivity gains that motivate industry to take actions toward adoption of EEMs. Others (36) focus their work on several entities who receive some benefit from the adoption of efficiency projects and found: utility, ratepayer and shareholder perspective, the societal perspective and the customer or participant ones. Factors are instead categorized by more recent works, since the adoption of structured frameworks has revealed to be a strong opportunity to explain the different nature of factors related to EEMs. Categories have been taken directly from the suggestions of industrial case studies review (36), or explore the diversity based on different key dimensions on the study's perspective (37). The primary role of non-energy benefits (production benefits) in end-user decision making process, is evidenced in previous research (35–38). The most recent literature studies focus on the rationale behind the choice of categories (5), (34) and underpin that the importance of factors is not correlated with their capability of being quantified. A second stream of literature gives information about EEMs in CAS, mainly addressed in documents by industrial practitioners. Energy efficiency manuals for compressed air (9), (11), (39) face the efficiency issue itemizing all the possible aspects that influence a specific measure through a series informative documents prepared for the most profitable EEMs, that serve as a guide to underline opportunities, both at components and systemic level. The focus on the specific technology gives advice about the main operational parameters that are modified by the EEMs adoption. Some works (9) (11) pointed out the most important data needed for a compressed air analysis, encompassing all others: pressure, temperature and mass flow rate and their variation in time, are revealed the most important.

As highlighted by recent studies (40), some of the perceived characteristics of EEMs are evaluated under too "ambiguous" criteria. It is difficult to categorize EEMs that are too general, and the trade-off in finding specific or general characteristics lies in the description of EEMs. On the one hand, if the framework is perceived as too general, there are not real possibilities of understanding what an adoption of a technology-specific EEM implies. On the other hand, the reference to a single technology, under a single perspective, by considering only one type of EEM (cross-cutting vs process), can result as too specific, and there will be the need of many of such tools to handle all the problems related to EEM adoption. In this regard, it should be remarked that, without the specification of a single technology, the work can lose the practical interest by industrial end-user (because too general to be applied for all EEMs). The specificity of this study relies in its orientation towards a specific technology and this, of course, may have an important influence on the decision of factors to fully characterize an EEM in CAS. As a consequence, despite the categories to which factors belong are fundamental for their characterization, this does not mean that factors are always found starting from a deep analysis of the three categories further introduced. In some cases, indeed, the decision upon the choice of one factor, comes from the technology revision of single EEMs. Therefore, some of the factors can be applied only to some types of EEMs. In this sense, the approach for considering such factors does not come from scientific literature on EEMs' characteristics, rather from a bottom-up analysis of industrial literature over CAS. In this direction, the work by Rogers (41) represents a milestone, as categories chosen to characterize the group of EEMs were applicable to both type of factors, without any exclusion. The bottom-up approach refers to this double side oriented nature of the framework for a specific technology, where some of the factors are derivable to the observation and analysis of technology-related EEMs and others from the thorough revision of scientific literature on general EEMs characteristics. Moreover, since the framework characterize deeply the EEMs, some of the factors can have different results when applied to different situations, i.e. in different firms.

FRAMEWORK: A PRELIMINARY PROPOSAL

Starting from the characteristics of the singular EEMs it is possible to develop a preliminary proposal of a more comprehensive framework to make a complete evaluation of each of them, for CAS equipment substitution or operative procedures. The types of macro-categories are basically three: the first ones are operational parameters, followed by economic-energetic considerations, fundamental and widely recognized as paramount important for the adoption decision of each type of EEM; the third part is addressed to the operative industrial context in which the adopted EEM will be embedded, that is the object of the research study. Categories' and factors' specifications should not make lose the sight of the final objective: to have a practical tool that can help in decision about CAS EEMs. This caveat is necessary to consider practical factors easily manageable from the site management or from who is in charge of making the decision.

Operational parameters

From industrial literature, all the main features and the relationship among the operational parameters are known. This section provides information on what the EEMs influence, affecting the main parameters and their variation in time. The needs for compressed air are defined by the *pressure* level and *flow rate* required by end-users in the plant (11), to which the *air temperature* is added, because of the many options in which it has an important role. It is worth noting that the chosen parameter does not represent only that item, rather represents a starting point from which the secondary parameters (indirectly influenced) should be considered. For instance, secondary parameters like heat and thermal capacity are directly linked to the air temperature; the pressure and flow rate related are power, work, but also volume, density and mass flow-rate of the air.

Economic and energetic parameters

As highlighted in the study by Fleiter et al. (34), profitability is the most important characteristic for the adoption of a technology, and to compare the profitability owned by EEMs, the *Internal Rate of Return* (IRR) is considered the stronger determinant. On the other hand, authors recognize how firms, in the vast majority of cases, prefer to use *payback period* as a simple investment decision rule for EEMs. The other prioritized factor for whatever type of investment is the *initial cost* (42), that may represent a major barrier hindering the adoption, as large literature shows (33). Fleiter et al. (34) pointed out that rather than the total expenditure, if it is required the passage from a technology or its efficient alternative, the initial expenditure should be substituted by the marginal cost. The amount of *energy saved* is the first indicator of savings coming from the adoption of an efficient alternative to be applied to the existing system, and thus used as third item in this category (5). The source of energy saved, despite industrial compressors may be driven by other sources, is almost always the electric one; on the other hand, pertaining waste heat recovery, the savings are quantified as the reduced heat energy consumption to supply.

Contextual parameters

Other than considering operative and economic-energetic parameters, the CAS EEMs can be further characterized by a series of "contextual parameters", strongly dependent on the industrial context in which an EEM will be embedded. Indeed, the context may have a big impact on how EEMs are perceived, thus thoroughly influencing the adoption decision-making process. As shown by Rogers (41), several valuable suggestions from the characteristics of innovations (in general terms) can be applied to the case of EEMs. In particular, taking inspiration from Rogers, three main categories of possible relevant factors could be identified: complexity, compatibility, and observability ones.

Complexity factors

Complexity is the degree of difficulty perceived when a measure is going to be adopted, and the increase of the complexity is generally negatively correlated with the adoption of an EEM (41). Understanding in which cases the EEM adoption is revealed to be complex is a fundamental passage to characterize it. The innovations' literature refers to the radicalness as an index of complexity, because it refers to the degree of change required for the adopters (43); in this case, the generality in defining the complexity (44), (34) is source of misunderstandings. For this reason, in this work, we look here at complexity as a wide category that can be further decomposed in different factors. An EEM is not complex a priori, but the impact its adoption implies, influences how complex it is perceived by industrial end-users. Among main complexity factors, we should for sure consider: *Activity type, Expertise required, Independency from other components/energy efficiency measures, Change in maintenance effort*, but also the *Accessibility*.

Compatibility factors

The compatibility axis explains to which degree the new measure to be adopted, can be adapted to the existing system, and this concept is strictly related to the flexibility concept. The compatibility factors refer to new technologies that should be adapted to the existing CAS or to a new state of the system applied to already existent technologies. Literature on compatibility characteristics (45) is referred more to innovations in general terms than on specific EEMs. Many of the studies, have not statistical inference about the compatibility of innovations, because of the objective difficulty in quantifying it. For Rogers (41), it can be referred to (i) the compatibility with the values and beliefs in some innovation, which does not apply to this model on the energy efficiency characteristics because is oriented on the cultural values that can hinder the adoption of a technology; (ii) the compatibility with the previously introduced ideas, that can be translated in previous adoptions towards some technology (technological compatibility), layout orientation or operating conditions that difficultly fits with new installation or retrofit in the system; (iii) compatibility with actual needs. Despite being relevant for the adoption, compatibility and possible derivate factors are not considered properly, because strongly dependent on the adopters' characteristics (34). Talking about a specific technology (i.e. compressed air), the focus is more oriented on the compatibility of the measure with the existing system i.e. to the fitting of the technology to install on the current system to the system itself. Potential adoption availability and adopters' efforts in coordinating activities are how the compatibility is re-interpreted in the field of EEMs. In this regard, it seems important to consider as relevant factors: *Technological compatibility, Presence of difference pressure loads at the end-use, Adaptability to different conditions, Synergy with other activities, Distance to the electric service*, as well as *Presence of thermal loads*.

Observability factors

Observability represent how an EEM, once implemented, can be perceived within the production context. The concept of observability of innovations is connected to the visibility and communicability to others (41), but in the narrower world of EEMs, the observability concept can be translated on what are the sensible changes detected in the working environment or to components, once the measure in implemented. Adapting interventions in an operative context, means contextualize them to see what is their degree of impact; in accordance with the academic literature, the concept of "implications on the existing system" is quite similar to studies pertaining non-energy benefits, coming from adoption of EE interventions. The impacts are usually described by literature as non-energy benefits, from the identification (46) to the effort to identify the quantifiability (47). 76 % of the CAS EEMs implementation experienced further (observable) benefits other than efficiency (48). The energy savings can also result in improved reliability of the system and support for production (49). But, taking inspiration from previous literature (50), in this work, we limit our considerations on factors, without considering whether they may have a positive (benefit) or a negative (loss) effect. Despite this, we acknowledge that some of the factors may be, for their own nature, more oriented towards one side and as consequence, the characterization of that measure should result easier. When considering observability factors, it seems important to consider: *Safety, Air quality, Wear and tear, Noise as well as Artificial demand.*

Concluding remarks and further research

In conclusion, in the present study we have tried to offer an overview of the main EEMs in CAS, so to get an insight about the main factors affecting the decision-making process to adopt them in the industrial sector. In particular, we have pointed out the need to develop an innovative framework to characterize and analyse such factors, by assuming an industrial decision-making perspective. Indeed, we believe that several attributes should be further detailed, starting from the extant literature. Furthermore, an at least explorative investigation of the framework seems to be needed, so to guarantee a proper validation of the novel approach and ensure that a good and useful tool for industrial decision-making purposes has been developed. We believe this validation would be a crucial phase to test the capability of the framework to thoroughly describe the set of main factors affecting the decision-making process over an EEM in CAS. Moreover, as further research, the framework could be used for empirical investigation within selected enterprises, possibly by clusters. This would get a useful understanding of commonalities and differences in terms of relevant factors when adopting an EEM in CAS. Finally, for policy-making purposes, the novel framework could be used for profiling different companies with respect to the adoption of EEMs in CAS, so to undertake the most appropriate strategies to support companies in overcoming barriers to the adoption of such EEMs.

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