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Energy Savings Measures in Compressed Air Systems

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ABSTRACT

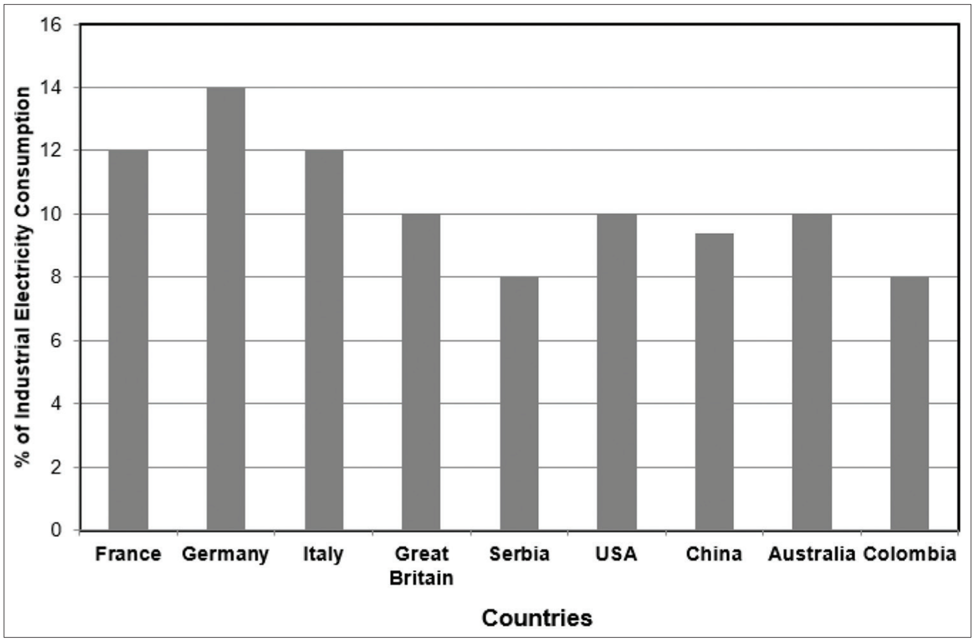
Compressed air is one of the most widely used application energies in the industry, such as good transportability, safety, purity, cleanliness, storage capacity and ease of use. In many countries, compressed air systems account for approximately 10% of the industry's total electricity consumption. Despite all its advantages, compressed air is expensive, only between 10% and 30% of the energy consumed reaches the point of final use. Energy is lost as heat, leaks, pressure drop, misuse, among others. Energy efficiency measures such as: reducing compressor pressure, lowering air inlet temperature, adequate storage capacity, recovering residual heat from the air compressor and reducing leakage, can produce energy savings between 20% and 60%, with an average return on investment lower than 2 years. This paper analyzes the main energy efficiency measures that can be applied in the CASs, the potential energy savings, implementation costs and return rate of each of them are being calculated giving a necessary tool for companies in their objectives to reduce greenhouse gas emissions and energy consumption.

Keywords: Compressed Air Systems, Electricity Consumption, Energy Efficiency, Energy Savings
JEL Classifications: Q47, L94, N66

1. INTRODUCTION

The compressed air systems (CASs) is one of the most widespread application energies uses in industry due to factors such as good transportability, safety, purity, cleanness, storability and easy use (Benedetti et al., 2018; Annegret and Radgen, 2003; dos Santos, 2019; Taheri et al., 2017; Yin et al., 2015). In many countries CASs require a considerable electrical energy consumption value of industrial electricity consumption. Figure 1 shows, the percentage of electrical energy consumption in countries as China, USA, Colombia, Australia and some Europe countries, (Saidur et al., 2010; Šešlija et al., 2011; Viholainen et al., 2015; UPME, 2013; UPME, 2014; UPME, 2014a). However, CASs is one of the most expensive form of energy, only among 10-30% of the input energy reaches the point of end-use (Kriel et al., 2014; Shaw et al., 2019). Energy is lost as heat, leaks, droppressure, inadequate uses, amongst others (Corsini et al., 2012; Abdelaziz et al., 2011). In a CASs, the energy consumption represents the 75% of their lifecycle cost, which is higher than initial investment 13% and maintenance 12% (Neale and Kamp, 2009; Vittorini and Cipollone, 2016). Energy efficiency measures, such as compressors pressure reduction, decrease air intake temperature, adequate storage capacity, air compressor waste heat recovery and leaks reduction, can produce energy savings between 20% and 60%, with a lower average payback of 2 years (Zahlan and Shihab, 2015; Bose and Olson, 1993; Cloete et al., 2013; Castellanos et al., 2019). The maintenance areas do not pay the same attention to the problems involved in the compressed air generation as they do to other, because CASs do not produce dirt, residues or accidents; and even though the widespread misconception of many experts whose think that CA is cheap. (Kaya et al., 2002), it causes that the only time of CASs get any

Figure 1: Industrial electricity consumption of CASs in different countries



Source: Prepared by the authors based on data from: (Benedetti et al, 2018; Šešlija et al., 2011; Saidur et al., 2010; UPME, 2013; UPME, 2014; UPME, 2014 a)

Nomenclature	
CA	Compressed Air
CASs	Compressed Air Systems
kWh_{CAS}	Electricity consumption in Compressed Air Systems (kWh)
kW_{TOT}	Total electricity consumption (kWh)
Tp	Total production in tonnes
EnPI	Energy performance index
T_{on}	On-load time of compressor (min)
T_{off}	Un-load time (min)
TL (%)	Total leakage in percentages
QL	Volumetric leak flow rate (m^3/h)
P_1	Normal operating pressure (kPa)
P_2	Half of operating pressure (kPa)
Po	Atmospheric pressure (Kpa)
AEC	Annual energy consumption in the CASs
SEC	Specific energy consumption, (kW/m^3)
OPH	Operating hours in year (h/year)
V	Total system volume (m^3)
V*	Relative receiver tank volume [m^3/(m^3/seg]
V_{AR}	Air receiver volume (m^3).
Q	Compressor flow rate (m^3/seg)
R_{AC}	Relative compressors air consumption
CAcon	Compressed air consumed in the system at work pressure (m^3/h)
CAcap	Compressed air possible to be generated by compressor at work pressure (m^3/h)
ES_{PR}	Annual Energy savings due to pressure reduction (kWh/year)
ES_{ARV}	Annual energy saving as a result of an adequate design of air receiver volume (kWh/year)
ES_{LP}	Annual energy savings due to leak prevention (kWh/year)
ES_{AIT}	Annual energy saving as a result of decrease in intake air temperature (kWh/year)
W_R	Fractional reduction in compressor work
T_1	Average temperature of inside air (°C)
T_0	Average temperature of outside air, (°C)
H_{RF}	Heat recovery factor

attention is when air and pressure losses interfere the normal operation of the process (Saidur et al., 2010).

All these factors lead that the CASs must be regarded as one of the main target systems for the implementation of energy efficiency actions in industry (European, 2009; Bonfàaet et al., 2017).

Further energy savings, increasing energy efficiency of CASs may ensure other Non-Energy-Benefits (NEBs). The most significant are: Increased and more reliable production, capital investment reduction, improved product quality and reduced maintenance; often, these benefits are more valuable than energy savings (Nethler et al., 2018; Nethler, 2018a; Fleiter et al., 2012).

The aim of this paper is to analyze the main energy efficiency measures that can be applied in CASs, calculating the energy savings potentials on them, the implementation costs and return rate. This is a very necessary tool for companies in their objectives to reduce energy consumption and greenhouse gasses emissions.

2. ENERGY MANAGEMENT

Energy management systems (EnMS)is considered one of the most efficient methods used to reduce energy consumption on industrial processes or at a company level (Abdelaziz et al., 2011). They are a systematic documented procedure with the objective on minimize energy costs., without affecting production and quality by defining objectives, policies and procedures that will be are maintained and improved (Schulze et al., 2016; Kanneganti et al., 2017). ISO 50001, supports the guidelines to develop an EnMS, based in a flexible framework that allow companies to integrate energy efficiency systems into their management practices (Angarita et al., 2019). The model covers four steps: energy policy, energy planning, implementation and checking, based on de Deming Cycle (Plan-Do-Check-Act), all of them are incorporated into a continuous improvement cycle as is shown in Figure 2 (Gopalakrishnan et al., 2014; ISO 50001, 2011; Correa et al., 2014).

2.1. Energy Policy

The energy policy is a statement of the company, which establishes a commitment in coherence with the nature and use of energy of the organization to achieve an improvement in energy efficiency. This policy defines a framework for action, sets the objectives and goals to be achieved and defines the resources for the purchase of products or services; it also establishes a commitment to ensure the availability of the required information. This declaration defines the multidisciplinary team to lead the implementation of the EnMS.

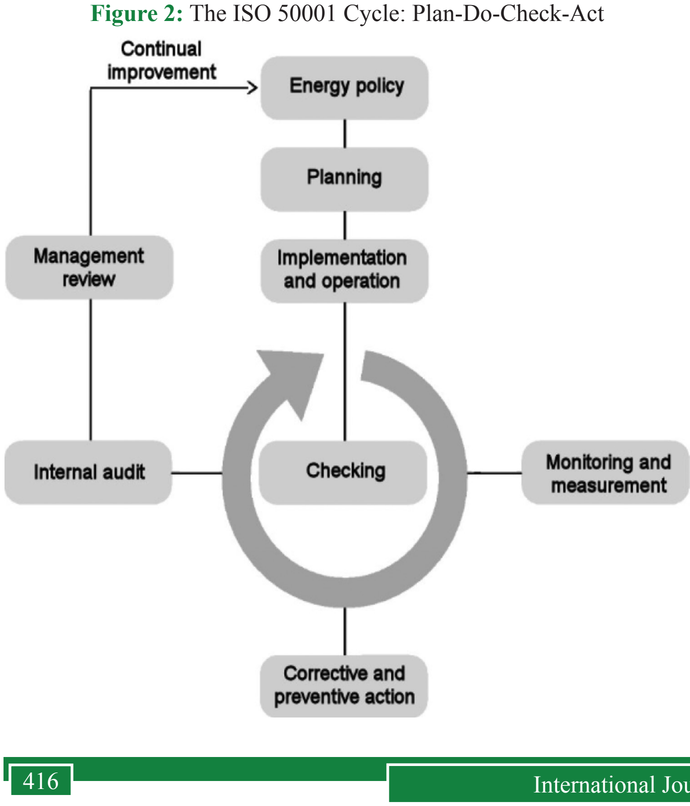
2.2. Energy Planning

It is a fundamental phase for the successful implementation of EnMS, some of the activities developed in this phase are: The identification of the main energy consumptions through the collection of historical information over production, operating parameters, flow diagrams and energy consumption. Identify the areas, equipment and variables that have the most influence on the company's energy consumption, as well as on its current energy efficiency. Identify the measures to be implemented in the systems and equipment to achieve an improvement in energy efficiency. Based on the information acquired in this process, it is possible to build the energy baseline, establish energy performance indicators (EnPIs) that allow proper management of energy use and consumption, establish the targets and action plans of the management system, determine investment costs and amortization periods of the different measures.

2.3. Implementation

This is the do part of the cycle and its main objective is to implement the measures proposed in the action plan. The company must ensure that the personnel executing the measures act according to the recommendations and have the necessary knowledge and skills. In order to do this, there must be a good communication within the organization, and it must control and conserve all the procedures used in the implementation.

Figure 2: The ISO 50001 Cycle: Plan-Do-Check-Act



2.4. Verification

In the verification stage, the company should supervise the progress of the targets established in the energy planning stage, according to the specifications defined for the equipment and processes to be followed, the frequency and the data collection method. This process can be developed through the following, control and systematic comparison of the evolution of the EnPIs with their respective baseline previously defined. If the organization does not achieve the proposed targets, it should review its relevance, or how the monitoring process was carried out to identify the cause of non-compliance. This should not discourage the organization, because it is also part of the continuous improvement process.

3. ENERGY EFFICIENCY MEASURES IN COMPRESSED AIR SYSTEMS

3.1. Compressed Air System

A CASs consists of two fundamental areas, supply and demand. On the supply side, the compressor is in charge of increasing the atmospheric air pressure to convert it into compressed air; a wet receiver tank, dryer, dry receiver tank and filters are responsible for lowering humidity and improving air quality. On the demand side, distribution lines and pressure and flow controls are responsible for bringing the amount of air to each equipment according to its consumption specifications. Figure 3 shows the main elements that compose a CAS.

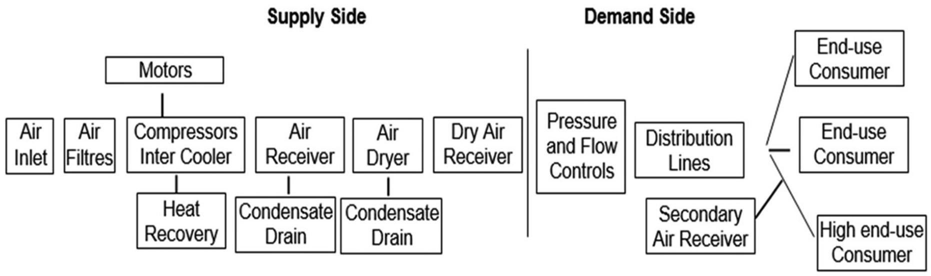
3.2. Incorrect Compressed Air Use

The production of CA is one of the most inefficient process in industry, only between 10% and 30% of consumed energy reaches the end use point (Mousavi et al., 2014). In industry exists the misconception that CA is inexpensive, encouraging its inappropriate use and causing a decrease in efficiency between 2% and 3% (Zahlan and Shihab, 2015), some examples of this uses are, open blowing, atomizing, padding, dilute-phase transport, dense-phase transport, vacuum generation, personnel cooling, cabinet cooling, vacuum venturis (DoE, U.S. 1998). The CA should only be used if safety, productivity, labor reduction, enhancements or other factors results significant (Kaya et al., 2002).

3.3. Location and Measurements of Leaks

Air leaks are the most significant cause of energy loss in CASs. In an adequate system, the values must be around 5-10% of the total CA production (European, 2009; Reddy et al., 2011a). However, in industrial systems the typically range of leaks is between 20% and 40% and without a correct maintenance and use, this could be to even 60% (Radgen and Blaustein, 2001; Abdelaziz, et al., 2011; Yang, 2009; Dudić et al., 2012). This cost represents the energy cost required to compress the loss of air volume from atmospheric pressure to the compressor operating pressure. Air leaks commonly appear in joints, flange connections, elbows, equipment connected to the compressed air lines, among others.

Figure 3: CAS and elements divided according to supply and demand sides



Source: Castellanos et al., 2019

In CASs heavy leaks are easy to hear, however, smaller leaks are harder to detect, the better methods used for this objective is ultrasound, or infrared technology (Dudić et al., 2012; Murvay and Silea, 2012; Paffel, 2017).

The amount of leakage in CASs can be measured by two methods. The first is for compressors that have an on/off or load/unload control, and consist in starting the compressor when there are no loads in the system. Leaks will cause a pressure drop, so the compressor will work in a load-unload cycle; the total leakage (TL) in percentages can be calculated as (Dindorf, 2012; Saidur, et al. 2010):

$$TL_{(\%)} = \frac{T_{on}}{T_{on} + T_{of}}.100 \quad (1)$$

In systems with other control strategies, if there is a pressure gauge downstream of the receiver, the air leaks can be calculated based on the system volume (V), that includes any downstream secondary air receivers, air mains and piping. The system without air demand, is started and brought to the normal operating pressure P1, afterwards, compressor is stopped and the time t(s) it takes to drop the pressure in the system to a value P2 about one-half the operating pressure is measured. Volumetric leak flow rate (QL) measured in (m3/s) can be calculated using equation 2: The 1.25 multiplier corrects leakage to normal system pressure.

$$Q_L\left(\frac{m^3}{s}\right) = V.\frac{(P_1 - P_2)}{P_0.\,t}.1,25 \quad (2)$$

The annual energy savings through leaks prevention can be expressed as:

ES_{LP} = AEC·TL%

In the on/off or load/unload controls

$$ES_{LP} = AEC \cdot TL\% \quad (3)$$

For other control, strategies

$$ES_{LP} = Q_L \cdot SEC \cdot OPH \quad (4)$$

3.4. Appropriate Design of Storage Capacity

The air receivers in CASs have several functions such as: Providing compressed air storage capacity to prevent short star/stop cycles of compressors, cooling compressed air with moisture condensation, covering pressure peaks periods, maintaining pressure in the system, allowing the control system to operate more effectively and improving system efficiency (European, 2009). The Kaiser company recommends the use of two receivers, one wet and other a dry receiver (K, 2010).The first one is located between the compressor and the dryer and the second one after the dryer (DoE, U.S. 1998). In some cases, it makes sense to use other receivers near to critical and high-pressure applications (Kaya, 2002).

The installation of an adequate storage capacity can reduce energy consumption. Figure 4 shows an example of savings in energy consumption (ES_{PC}) caused by increasing the relative receiver tank volume (V*) between the minimum and optimal values recommended by manufacturers, [12m3/(m3/seg) to 120 m3/(m3/seg)], for a system with 40% of relative compressed air consumption (RAC). (Kluczek and Olszewski, 2017; Olszewski and Borgnakke 2016). V* and the RAC can be obtained using equations 5 and 6.

$$V^* = \frac{V_{AR}}{Q} \quad (5)$$

$$R_{AC} = \frac{CA_{con}}{C_{cap}} \quad (6)$$

The Annual energy saving through an adequate air receiver volume can be expressed as:

$$ES_{ARV} = AEC.ES_{PC} \quad (7)$$

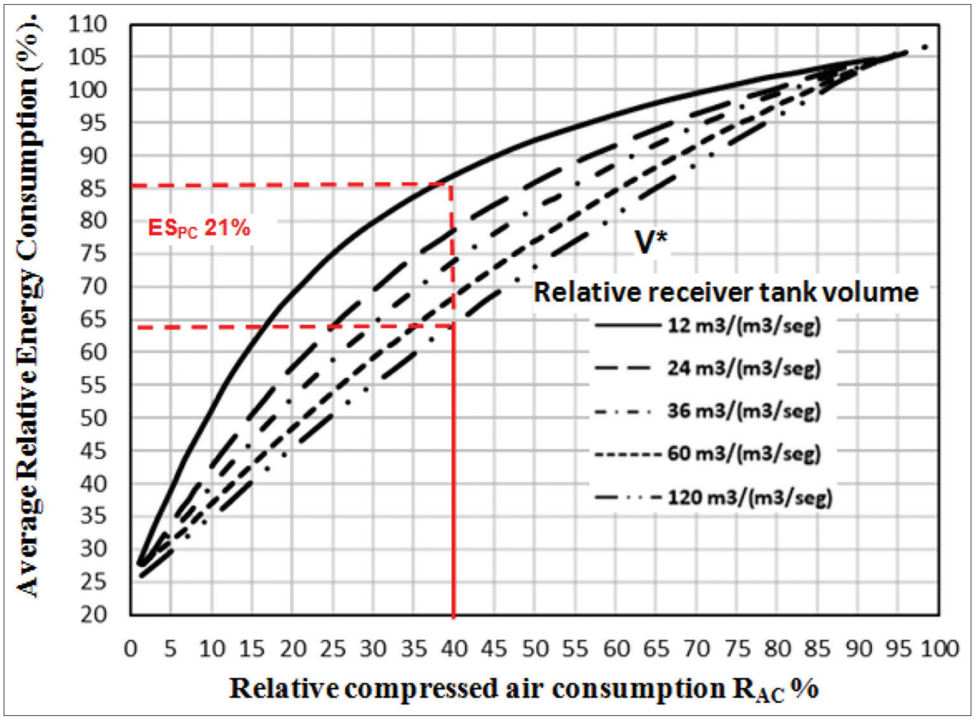
3.5. Analysis of Systems Pressure Drop

In industry, CASs require a certain pressure and flow to support the process; this is often handled by a regulating system. Most CASs have equipment or applications that define the minimum pressure value required. When the system is pressurized to this value and only a small percentage of devices require this high pressure, it causes a waste of energy.

Dividing the network into areas, to create a system with several pressure values, and reducing the pressure to the lowest level required in each one, is a form to save energy (Abdelaziz et al., 2011; Dindorf, 2012). Another strategy is to design a system that offers lower pressure and add pressure boosters for equipment or applications that require higher pressure values (Radgen and Blaustein, 2001).

In a properly designed and maintained CASs, pressure drops between the air receiver tank and end use points must be <10% (DoE, U.S. 1998). In many cases, these values are higher due to obstructions,

Figure 4: Relative energy consumption for different relative receiver tank volumes as a function of relative compressed air consumption



Source: Taken from Olszewski and Borgnakke; 2016 and modified by the authors

restrictions and system components, causing the malfunction of some equipment and components. Against this background, the most common action applied in the industry is to increase the output pressure of the compressor, without consider that this measure increases electricity consumption. Figure 5 shows an example of the decrease in energy consumption caused by the pressure reduction in an industrial system with air operating around 8 bars. Reducing the pressure in 1.5 bar give 12% reduction in energy consumption. In addition, consumption in unregulated end uses decreases between by 4% and 7% (DoE, U.S. 1998). The combined effect gives the total energy savings (TES_{PR}) between 16% and 19%.

Other measures related to pressure, aimed to reduce energy consumption are:

- To select the air treatment components with the lowest possible pressure drops.
- To install a ring main in systems with a larger numerous of take-off points.
- To optimize the location of the air compressor, the distance to the areas of greatest demand and pressure should be minimized.
- The distribution system designed should consider a low-pressure drop between the compressor and the location of its use.

The annual energy savings due to pressure reduction can be expressed as follow:

$$ES_{PR} = AEC \cdot TES_{PR} \quad (8)$$

3.6. Intake Air Temperature

Compressors are usually located on premises inside the facilities or in adjacent shelters specifically built for them. The air is normally taken from the inside of these buildings at higher temperature than outside, due to the dissipated heat from the compressors and its motors. At higher temperatures, the compressors must work harder to compress the hot air, decreasing their efficiency. Therefore,it is advisable to take the air from outside and install a duck for this function in case to be required. The fractionated work reduction in compressor WR due to reduction of intake air temperature can be estimates as (Kaya, 2002; Saidur et al., 2010):

$$W_R = \frac{T_1 - T_0}{T_1 + 273} \quad (9)$$

The annual energy savings through intake air temperature reduction can be expressed as:

$$ES_{AIT} = AEC \cdot W_R \quad (10)$$

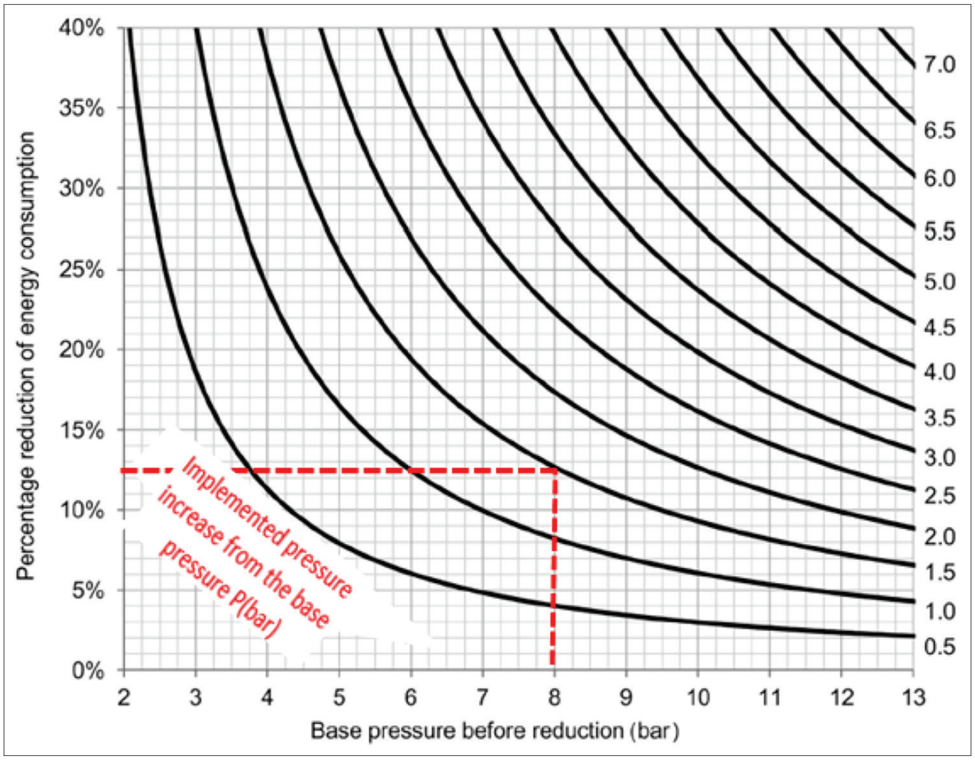
3.7. Heat Recovery

In an industrial CASs, about 80-93% of the electrical energy consumed is converted into heat, which can be used for space heating, industrial drying, preheating aspirated air for oil burners, in central heating or boiler systems, industrial cleaning processes, heat pumps, laundries, or any other application where hot air or hot water are required (Broniszewski and Werle, 2018; Huang et al., 2017; Goodarzia et al., 2017). A properly design heat recovery unit can have a recovery factor between 65% and 75%. The configuration of the compressors package helps to heat the recovery process, the only modifications in the system required are the addition of ducting and possibly another fan to handle the duct load and eliminate any back pressure in the compressor cooling fan. As a rule, approximately 312.7 kWh of energy is available for each m3/seg of capacity.

Annual energy savings associated with heat recovery.

$$ES_{AI} = AEC \cdot H_{RF} \quad (11)$$

Figure 5: Energy consumption reduction by lowering the output pressure



Source: Taken from Olszewski and Borgnakke; 2016 and modified by authors

3.8. Energy Performance Index and Benchmarking in CASs

A correct handling of energy consumption in facilities, require the definition and management of energy performance indexes (EnPI), the use of benchmarking as tools to improve efficiency and performance through continuous evaluation process, in different operating conditions and time frames. The identification of inefficiencies in energy use and estimating the energy saving potential; can also be used to compare the energy performance against its peers and they might promote improvement actions in areas where the company requires actions (Corsini et al., 2015; Madrigal et al., 2018; Shim and Lee; 2018).

In companies, designing a reliable EnPI that allow an adequate monitoring of the system can be a simple or complex process (Bonacina, 2015. According to (Goldstein and Almaguer; 2013), it is a common problem the incorrect design of EnPIs, which can lead to an incorrect interpretation of the company's energy behavior. Several studies have been developed to obtain an appropriated (EnPI) for different industries and process.

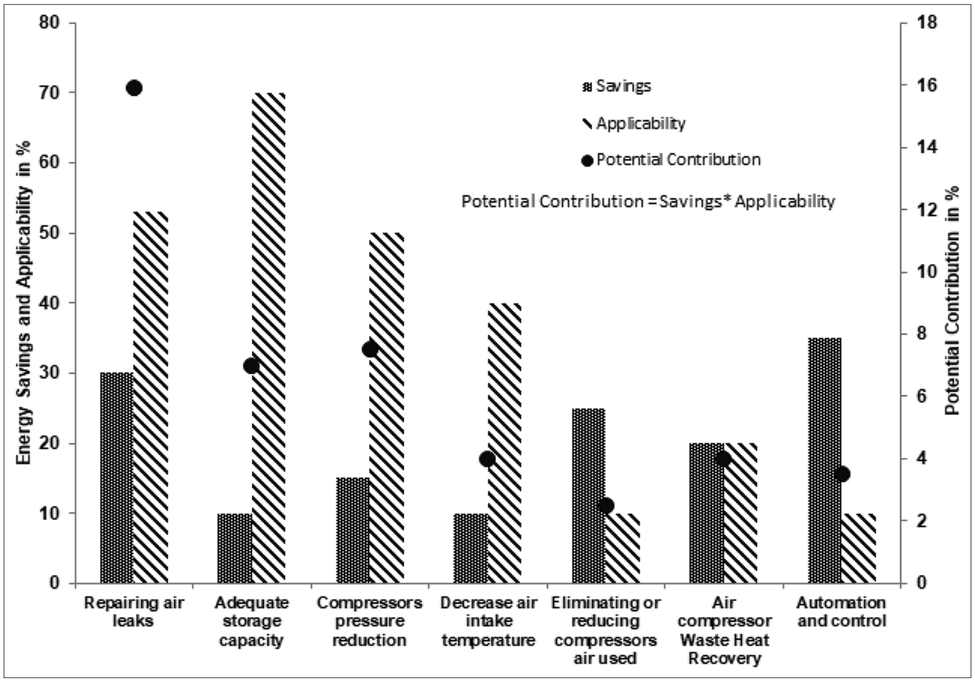
In Cabello et al; 2019, it is proposed an EnPI that allows to measure the energy consumption in a battery formation process, while in (Sarduy et al., 2018) is obtained an EnPI during the flour production process, particle size and added water for softening wheat in a Wheat Mill Plant. Other authors as (Anderson et al., 2018; Festel, and Würmseher, 2014) reports in their studies a list of some selected EnPIs than can be used for in industrial sectors.

The typical (EnPI) proposed by (European, 2009; Corsini et al., 2015; Dindorf, 2012; Mousavi et al., 2014) to verify the performance of CASs is the specific energy consumption (SEC). In (European, 2009; Dindorf, 2012) is defined that for a correctly dimensioned and well managed facility, operating at a nominal flow and at a pressure of 7 bars this value can be between 85 and 130 Wh/m^3. Others EnPI indicators proposed by (Benedetti et al., 2018) specify the ratio between the amount of energy consumed to produce compressed air and the total electricity consumption (kWhCAS/kWhTOT) and the ratio between the amount of energy consumed to produce compressed air and the production volumes (kWhCAS/tp). In (Corsini et al, 2015) was proposed a performance indicator that relates air volume with mass of raw material (m^3/kg). A study developed by Anglani and Mura in different companies from various industrial sectors leads to the conclusion that EnPI and benchmark values in CASs should be defined per each industrial sector.

4. DISCUSSION

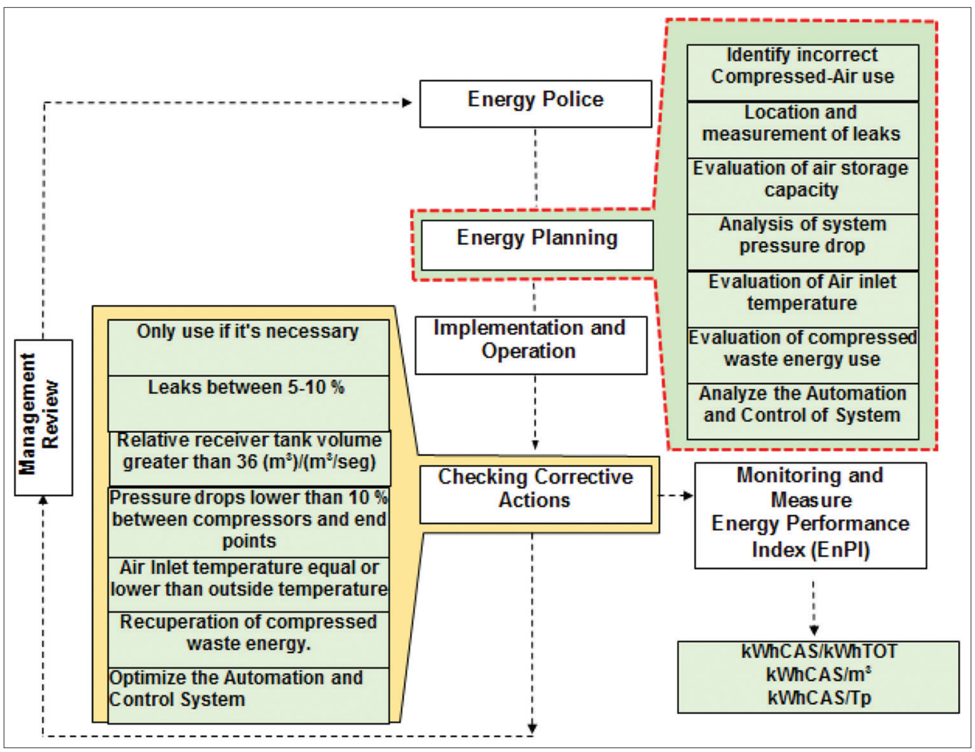
Based on the literature review, there are different energy efficiency measures that can be applied to CASs in order to reduce energy consumption. Authors such as (Saidur et al., 2010; Slodoban et al., 2012) consider leaks as the major cause of losses in CASs with values between 20% and 40%, while (Benedetti et al., 2018; Radgen and Blaustein, 2001) consider them as a second place after an inappropriate use which they estimate a saving potential of 25%. The recovery of wasted heat is another measure in which many authors are agree that between 70% and 80% can be recovered with an applicability between 10% and 20% lower than the 35% established for leaks. Pressure reduction and proper sizing of air receivers has a low savings potential but a greater

Figure 6: Energy saving, applicability and potential of contribution for different improvement measures in CASs



Source: Prepared by the authors based on data from Benedetti et al, 2018; Saidur et al., 2010; Šešlija et al., 2011

Figure 7: Model of the energy management system ISO 5001 adapted to a CASs. Information prepared by the authors based on ISO 50001



applicability, so they are also interesting measures. Figure 6 shows the potential savings for different measures, their applicability and contribution to the reduction of electricity consumption of CASs.

The electricity consumption reduction in CASs can be achieved through the implementation and proper management of a system for Efficient Energy Management where all measures are analyzed and correctedto reduce consumption. Figure 7 provides a model for efficient energy management based on ISO 50001 for a CASs. The main aspects of each one of the stages are mentioned, the goals and objectives that must be drawn up for each of the measures are proposed.

5. CONCLUSIONS

CASs are widely used in the industrial sector, consuming about 10% of the electricity bill, however is one of the most inefficient systems since only between 10% and 30% reaches the end point use, applying energy efficiency measures in this system can provide savings between 20% and 60% with an average payback lower than 2 years.

Some of the measures that can be implemented are: Reduce the unsuitable use of compressed air, reduce the compressors pressure, decrease air intake temperature, guarantee an adequate storage capacity, recover waste heat from the air compressor and reduce leakage. From the above measures highlighted the highest contribution values to guarantee the reduction of electricity consumption in terms of potential savings and applicability are the reduction of leaks, the pressure reduction and an adequate storage volume in that order.

The implementation of an efficient energy management system based on ISO 50001 would allow these measures to be properly implemented and maintain the system working with minimum electricity consumption values.

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