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Energy efficiency in the industrial compressed air systems: an explorative investigation of interventions, barriers and drivers

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ABSTRACT

Climate change is the most severe problem that we are facing today, more serious even than the threat of terrorism.

Sir David King, UK Government's Chief Scientific Adviser
9 January 2004

Policy makers worldwide have recognised energy efficiency to be an effective means to satisfy the growing energy demand and reduce greenhouse gases emissions, in order to secure a sustainable economic development. This dissertation focuses on the energy efficiency of the compressed air, such an essential aid to the manufacturing and process industries to be often called the "Fourth Utility". The production of compressed air can be one of the most energy consuming processes taking place in an industrial facility, and it is well acknowledged the existence of an unexploited energy efficiency potential. To address such problem, the present thesis discusses the Energy Efficiency Measures (EEMs) recommended by the U.S. Industrial Assessment Centres (IAC) and the results obtained from several descriptive analyses of the IAC Database. It also presents the main findings from an explorative investigation among different types of manufacturing companies in Lombardy. The preliminary results suggest that some energy efficiency interventions are scarcely adopted, such as waste heat recovery from the compressor. Also, firms' attitude towards the energy efficiency of their compressed air installations is quite uneven throughout the industry. Small enterprises (SEs) implement EEMs to a much lower extent than larger companies, with the gap becoming critical for the more expansive interventions, such as the purchase of a new compressor and related control system. Organisational barriers, such as lack of time, are considered the most critical issue, especially by SEs. The results also highlight lack of competences to be a strong factor limiting the energy efficiency in the small companies. Policy makers are called to design effective policies to overcome these issues. The regulatory framework should then include both technical support schemes and economic subsidies for investments in energy efficiency.

KEY WORDS: industrial energy efficiency, compressed air, EEMs, barriers, drivers.

SOMMARIO

Il cambiamento climatico è il problema più grave che stiamo affrontando oggi, più grave perfino della minaccia del terrorismo.

Sir David King, Primo Consigliere Scientifico del Governo del Regno Unito
9 gennaio 2004

Le autorità politiche di tutto il mondo hanno riconosciuto che l'efficienza energetica è un mezzo efficace per soddisfare l'aumento della domanda di energia e ridurre le emissioni di gas serra, in modo tale da assicurare uno sviluppo economico sostenibile. Questa tesi si concentra sull'efficienza energetica dell'aria compressa, un supporto fondamentale alle industrie manifatturiere e di processo. La produzione di aria compressa può essere una dei processi più energivori che hanno luogo in un impianto manifatturiero ed è ampiamente documentata l'esistenza di un potenziale di efficienza energetica non sfruttato. Per affrontare tale tema, questa tesi discute le misure di efficienza energetica (EEMs) raccomandate dall' ente americano Industrial Assessment Centers (IAC) e i risultati ottenuti da diverse analisi descrittive del database IAC. Essa presenta inoltre i principali risultati ottenuti da un'investigazione esplorativa tra diverse tipologie di aziende manifatturiere in Lombardia. I risultati preliminari di tale investigazione suggeriscono che alcuni interventi di efficienza energetica sono scarsamente adottati, tra i quali il recupero del calore dal compressore. Inoltre, il comportamento delle aziende nei confronti dell'efficienza energetica delle loro installazioni di aria compresa è piuttosto variabile nell'industria. Le piccole imprese (PI) implementano misure di efficienza energetica in misura minore rispetto alle aziende più grandi, ed il gap diventa critico per gli interventi più costosi, come l'acquisto di un compressore nuovo e del sistema di controllo. Barriere di natura organizzativa, come la mancanza di tempo, sono considerate i fattori più critici, specialmente dalle piccole imprese. I risultati evidenziano anche che la mancanza di competenze è un fattore che limita l'efficienza energetica nelle piccole aziende. Le autorità regolatrici sono chiamate a creare politiche efficaci per superare tali problemi. Il contesto regolativo dovrebbe quindi includere sia schemi di supporto tecnico che sussidi economici per gli investimenti nell'efficienza energetica.

PAROLE CHIAVE: efficienza energetica industriale, aria compressa, EEMs, barriere, driver.

CHAPTER 1 – INTRODUCTION

1.1 Energy outlook

The U.S. Energy Information Administration (EIA) annually prepares one of the most authoritative reports providing data on the contemporary international energy situation, as well as projections of future developments of the energy markets. Figure 1 retrieved from the International Energy Outlook 2016 (EIA 2016) shows that the global energy consumption has been dramatically increasing since 1990, reaching the value of almost 550 quadrillion British thermal unit (Btu) in 2012. Since 2008, non-OECD nations have surpassed the energy demand of the developed economies.

The agency forecasts rising trends also over the next three decades, projecting in 2040 a global energy consumption 48 percent higher than in 2012. This trend is mainly driven by the economic and population growth of the non-OECD nations (mainly China and India), whose energy consumption is expected to rise of more than 70 percent between 2012 and 2040.

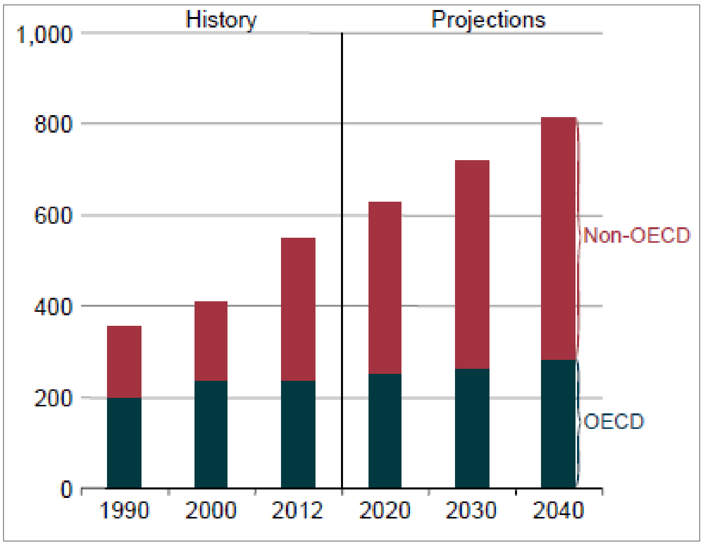

Figure 1 - World energy consumption, 1990-2040 [quadrillion Btu] (EIA, 2016)

Currently, most of the world energy demand is fulfilled by fossil fuels, which represent the lifeblood of the modern society. Liquid fuels are the primary energy source satisfying about 33 percent of the global energy demand, followed by coal (about 28 percent) and natural gas (about 23 percent). Due to concerns about the security of energy supply and environmental consequences of greenhouse gas (GHG) emissions, governments are working to reduce their dependency on fossil fuels. As a consequence, their share is expected to decrease in future, even though they still will account almost 80 percent of the energy use in 2040. Natural gas, the least carbon-intensive fossil fuel, is projected to surpass coal by 2030 and cover about one fourth of the energy demand in 2040 (Figure 2).

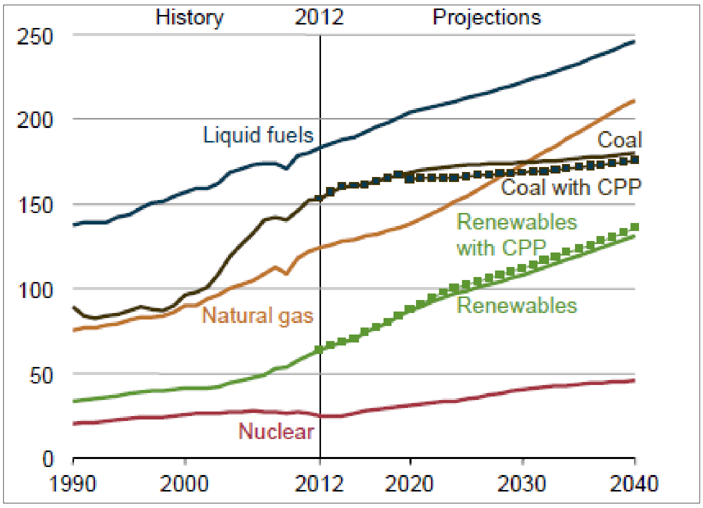

Figure 2 - World energy consumption by energy source [quadrillion Btu] (EIA, 2016)

This extensive use of fossil fuels poses two main questions: "how long can we go on with fossil fuels?" and "which is the environmental impact?". Many analysts consider the finite nature of fossil fuels to be a long-term problem, even though there are some of them who consider it a short-term issue. The estimates of fossil fuels' reserves that can be cost effectively exploited are extremely complex, as they depend on new discoveries, technological progress, and volatility of fuel prices. Because most of fossil fuels' reserves are located in regions of the Earth which are politically unstable (e.g. the Middle East), fossil fuel supply could be constrained at any time by geopolitical events. In this regard, the possibility to use fossil fuels is irrespective of the physical availability of oil and gas in the ground. Anyways, if the exact date of oil peak production is doubtful, there is no dispute that it is inevitable, and because it may be known only after the event occurs, governments need to be prepared (Fawkes 2007).

Besides the availability of fossil fuels, there is the issue of climate change, which is nowadays an accepted fact. In fact, even if fossil fuels were in greater abundance, their continuous consumption in the future would lead to a massive increase in carbon dioxide (CO2) and other GHG, and hence an accelerated global warming. The Reference Case of the International Energy Outlook 2016 forecasts world energy-related CO2 emissions to rise from about 32 billion metric tons in 2012 to more than 43 in 2040. Much of this growth is attributed to the developing non-OECD nations, many of which continue to strongly rely on fossil fuels to meet their increase of energy requirements.

Examining the consumption of the delivered energy[1] across the end-use sectors, it is apparent the dominant role of the industrial sector. It is in fact the largest single energy user, consuming about 54 percent of the world's delivered energy (EIA 2016). Furthermore, industry is responsible for 21 percent of the global GHG emissions due to direct industrial activities. Considering its share of indirect emissions related to electricity and heat consumption, the industrial sector overall accounts for more than 30 percent of GHG emissions (EPA 2016).

According to the Reference Case of the (EIA 2016), industrial energy consumption will increase by an average of 1,2 percent/year, leading by 2040 to a demand of 309 quadrillion Btu. This trend is fostered by the impressive growth of the industry in the non-OECD countries, that in 2040 are expected to account for 73 percent of the global industrial energy demand.

1.2 The importance of energy efficiency

The concept of energy efficiency refers to using less energy to produce the same amount of services or useful output. Energy efficiency should be distinguished from energy conservation, which instead refers to the action of saving energy by lowering the level of a service.

Many governments around the world share the policy goal of improved energy efficiency, as it is recognised to be one of the most effective means to tackle the issues described in the previous paragraph. The benefits of a more efficient use of energy include: reduced investments in energy infrastructures, lower fossil fuels' dependency, increased national competitiveness, and improved consumer welfare (IEA 2008). Of course, efficiency gains also deliver environmental benefits by reducing GHG emissions and local air pollution. The most enlightening explanation of the great

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[1] Delivered energy does not include losses associated with electricity generation and transmission (EIA 2016)

importance of energy efficiency can be found in the Energy Efficiency Directive 2012/27/EU of the European Parliament:

"The Union is facing unprecedented challenges resulting from increased dependence on energy imports and scarce energy resources, and the need to limit climate change and to overcome the economic crisis. Energy efficiency is a valuable means to address these challenges. It improves the Union's security of supply by reducing primary energy consumption and decreasing energy imports. It helps to reduce greenhouse gas emissions in a cost-effective way and thereby to mitigate climate change. Shifting to a more energy-efficient economy should also accelerate the spread of innovative technological solutions and improve the competitiveness of industry in the Union, boosting economic growth and creating high quality jobs in several sectors related to energy efficiency." (The European Parliament anf the Council of the European Union 2012).

For manufacturing companies, higher energy efficiency brings several direct and indirect benefits. First of all, it allows to save on energy costs, and lower the yearly operative costs. Furthermore, it also ensures a broad set of non-energy benefits, such as: reduced waste, lower emissions, improved maintenance and operating costs, increased production and product quality, improved working environment and greening of company image (Worrell et al., 2003).

When talking about energy efficiency, one of the major problems is how to measure it. In fact, energy efficiency is a generic term, and there is no one unequivocal quantitative measure of the energy efficiency level. Instead, a series of indicators can be used to quantify changes in energy efficiency. These fall into four main groups: thermodynamic, physical-thermodynamic, economic-thermodynamic and pure economic (Patterson 1996).

At national or sectoral level, one of the most commonly used is the Energy Intensity, calculated by the ratio final energy consumption over Gross Domestic Product (GDP). However, this indicator has been widely criticised, as it does not measure the underlying technical energy efficiency. For example, the structure of the economy of a country greatly impacts on its energy intensity: a nation with an industrial economy will have higher energy intensity than a country based on the tertiary sector, but it does not necessarily mean it is less efficient. Also climate affects energy intensity: cold and hot regions consume considerable more energy than temperate countries, especially for buildings' heating and conditioning.

In order to overcome the bias introduced by such factors, the ODEX indicator has been designed within the framework of the Odyssee-Mure Project[2]. The ODEX represents a better proxy for assessing the energy efficiency trends at an aggregate level (e.g. overall economy, industry, households, transport, services) than the traditional energy intensity indicators, as they are cleaned from the effect of structural changes and other factors not related to energy efficiency (Definition of Energy Efficiency Indicators in ODYSSEE database 2012).

Figure 3 shows the energy efficiency progress of the different sectors in the EU measured by the ODEX indicator. Values of the ODEX lower than 100 indicate improvements of energy efficiency with respect to the 2000 level. As it can be seen, energy efficiency improved by about 1,2 percent/year on average from 2000 to 2013 at the EU level (for a total of 15 percent improvements over the period). However, the pace of progress has slowed down since the economic crisis: the annual gain has dropped from 1,3 between 2000 and 2007 to 1 percent/year between 2007 and 2013, mainly due to the productive sectors (industry and transport).

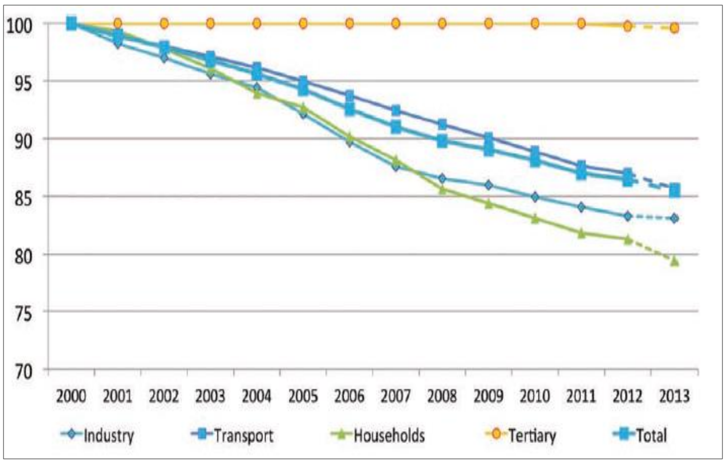

Figure 3 - ODEX trends in the EU (ODYSSEE-MURE PROJECT, 2015)

In fact, the pace of industrial energy efficiency improvements has been divided by two since 2007 (1 percent/year since 2007, compared to around 2 percent/year between 2000 and 2007). This change in the historical trends could be explained by the fact that energy consumption reduces less than proportionally when production declines, mainly for two reasons: the efficiency of the

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[2] The Odyssee-Mure is an international project co-founded by the Intelligent Energy Europe programme of the European Union, carried out thanks to the cooperation of 32 partners from 27 countries from EU Member States and Norway. The project relies on two complementary internet databases, ODYSSEE and MURE, that are regularly updated by the network of national teams. The data are publicly available at the website http://www.odyssee-mure.eu/.

equipment drops if it is not used at full capacity, and part of the energy consumed is independent of the production level (e.g. space heating and lighting).

These data clearly show that although Europe is more efficient today than it was in the past, the rate of improvement is alarmingly slowing down, with the industry being one of the worse-performing economic sectors over the last decade. An analysis by industrial branch reveals that energy efficiency improvements are quite uneven within the industry (Figure 4).

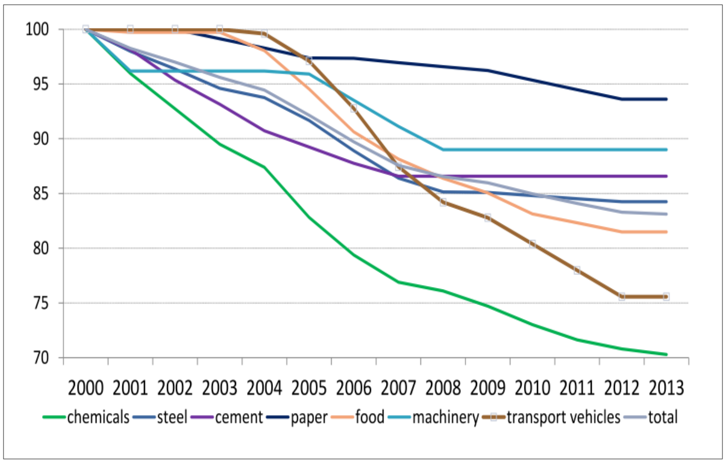

Figure 4 - ODEX trends in the UE by industrial sector (ODYSSEE-MURE PROJECT, 2015)

In the chemical sector energy efficiency has been steadily enhancing since 2000, leading to an improvement of 30 percent over the period 2000 - 2013. Higher energy efficiency can be appreciated also in the transport vehicles since 2004, resulting in a 25 percent improvement. On the other hand, the paper branch shows the poorest performances, with only a 6 percent improvement with respect to 2000 level. The remaining sectors, such as steel, cement, food, and machinery, have good improvements within the range 11 - 18 percent, but all of them (except food) show a marked drop in the efficiency gain since the years 2007 - 2008.

In March 2007, EU Member States decided to transform Europe in a highly energy-efficient, low-carbon economy and agreed on the so-called “20-20-20” targets, which became official in 2009 with the “Climate and Energy Package”. The Climate and Energy Package is a set of binding legislations which aim to ensure that the EU meets its challenging climate and energy targets for 2020 (Bertoldi et al., 2015). This includes three key objectives:

- a 20% reduction of EU greenhouse gas emissions from 1990 levels;
- a 20% share of EU energy consumption produced from renewable resources;

- an improvement in the EU energy efficiency to achieve a 20% savings on the primary energy consumption.

Recently, the European Commission performed an assessment of the progress achieved by the Member States towards the national targets. The results indicate that, even though important improvements have been accomplished, the EU energy efficiency target will not be met by 2020 at the current peace (The European Parliament anf the Council of the European Union 2015).

In this scenario, a critical role is played by small and medium-size enterprises (SMEs). These represent the vast majority of the total number of enterprises (often more than 99 percent), and often have a level of energy efficiency dramatically low. The Observatory of European SMEs has reported that *"the overall picture is surprisingly unfavorable: close to two thirds of SMEs operating in the EU do not even have simple rules or devices for energy saving (63%). Less than three in 10 SMEs (29%) have instituted some measures for preserving energy and resources at their enterprise. Only 4% of EU SMEs have a comprehensive system in place for energy efficiency"* (European Commision 2008).

Hence, despite the promising results achieved so far, it is apparent that further effort is still necessary to fully achieve the EU energy efficiency targets, and that much more attention should be paid to the SMEs, responsible for a significant portion of the so-called energy efficiency gap.

1.3 The problem: the energy efficiency gap

Several studies agree that the energy saving potential to improve energy efficiency already exists but it remains unexploited. As a result, energy efficiency is lower than it could (and should) be. The difference between the actual implemented level of energy efficiency and what is perceived as the optimum level is a widely known problem, which is often referred to as "energy efficiency gap" (Hirst & Brown 1990).

In order to estimate the magnitude of such gap, a conceptual question is how to define the optimal level of energy efficiency. (Jaffe & Stavins 1994) identified five levels of optimum, and hence five possible values of energy efficiency gap: the economists' economic potential, the technologists' economic potential, the hypothetical potential, the narrow social optimum and the true social optimum.

Based on their work, in the Third Assessment Report the Intergovernmental Panel for Climate Change (IPCC 2001) developed a framework distinguishing four levels of energy efficiency. The bottom line is labelled market potential, and it represents the current level of energy efficiency, as well as the future one under forecast market conditions, with no changes in policy. At the other extreme, there is the technical potential, which is the maximum potential achievable if all energy efficient technologies were implemented. In between there are the economic and the socioeconomic potentials, which are both considered as cost-effective, but under different perspectives. The economic potential reflects the consumer's point of view: cost-effectiveness is evaluated using market prices and private discounting rates. The socioeconomic potential, instead, represents the level that would be achieved if all technologies that are cost effective (on the basis of a social rather than a private rate of discount) are implemented, without regard to existing concerns about their performance characteristics.

The gap between the market potential and the cost-effective potential (from an individual or social point of view) is explained by the existence of several barriers to energy efficiency. A formal definition of barrier is provided by (Cagno et al., 2013), who define a barrier as *"a postulated mechanism that inhibits investment in technologies that are both energy efficient and (apparently) economically efficient, without the necessity that one or more other barriers occur".* In simple terms, barriers are the reasons why energy efficiency interventions are not undertaken, even when they could be profitable.

Another important remark is that the energy efficiency gap has been historically treated as a pure technological problem, with governments instituting policies and supporting schemes for the adoption of energy efficient technologies. However, several studies have recently shown that the potential for energy efficiency improvement is much larger if good energy management practices support efficient technologies. In this regard, (Backlund&Thollander, 2012) introduced the concept of "extended energy efficiency gap", considering the energy efficiency improvements stemming from both technologies and practices. The authors distinguish then two types of barriers, those hindering the diffusion of hardware technologies, from those inhibiting the implementation of an effective energy management program (Figure 5).

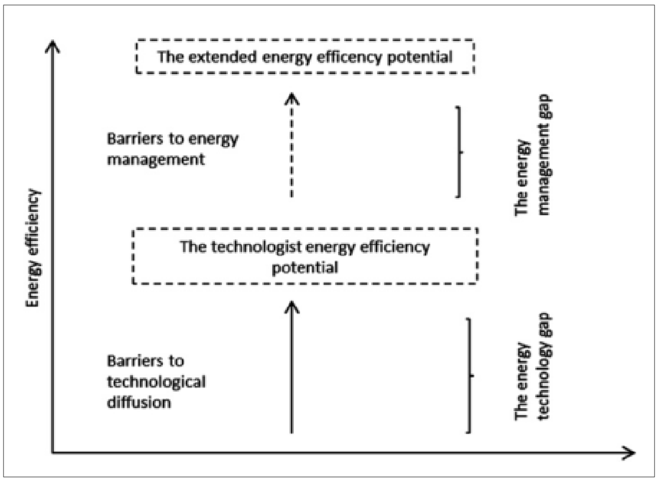

Figure 5 - The extended energy efficiency gap (Backlund et al., 2012)

If on the one hand barriers are the problems that companies face and which hinder them to improve their energy efficiency, on the other hand drivers are those forces that stimulate companies to undertake the energy efficiency measures (EEMs). The academic discussion on energy efficiency drivers is considerably less structured and less ample than the one on the barriers. One of the most important contributions to the research on this topic has been recently offered by (Trianni et al., 2016). Among the other inputs, the authors have provided an original and clear explanation of what drivers are, defining them as "*factors promoted by one or more stakeholders, stimulating the sustainable adoption of energy-efficient technologies, practices and services, influencing a portion of the organization and a part of the decision-making process in order to tackle existing barriers*".

1.4 Why compressed air

This paragraph is intended to illustrate how compressed air fits in the energy frame analysed in the previous sections. First of all, compressed air is just atmospheric air at higher pressure: once pressurised, air becomes an energy carrier. In fact, pressure is a form of potential energy, which is stored in the air and used when needed. There are three basic reasons why energy efficiency of industrial compressed air systems is a subject of utmost importance:

1. compressed air can be found in virtually all manufacturing plants;
2. compressed air represents a significant share of the industrial electricity consumption;
3. there is a large unexploited energy efficiency potential in compressed air systems.

1. WIDE USE THROUGHT THE INDUSTRY

Compressed air is often called "The Fourth Utility" because it an essential aid to millions of manufacturing companies around the world. Compressed air also plays a vital role in many non-manufacturing sectors, including the transportation, construction, mining, agriculture, and service industries. However, unlike electricity, water and gas utilities which are generated and supplied by external plants, compressed air is something that end users have complete control of. This gives rise to issues such as availability of competencies and time to adequately design and manage a plant which is often not part of the core business of a company. There are several good reasons why compressed is so largely employed, such as (CAGI 1998):

- ease-of-production: “you just need a compressor” to produce compressed air;
- availability: compressed air can be stored using tanks located in places where no other power is available or practical;
- safety: compressed air can be used where other energy sources cannot be used due to explosion hazard or fire risk;
- cleanness: compressed air is suitable for applications where quality, hygiene and safety are essential; and
- ease-of-use: air tools are often lighter than the equivalent electrical models, making them easier for an operator to handle.

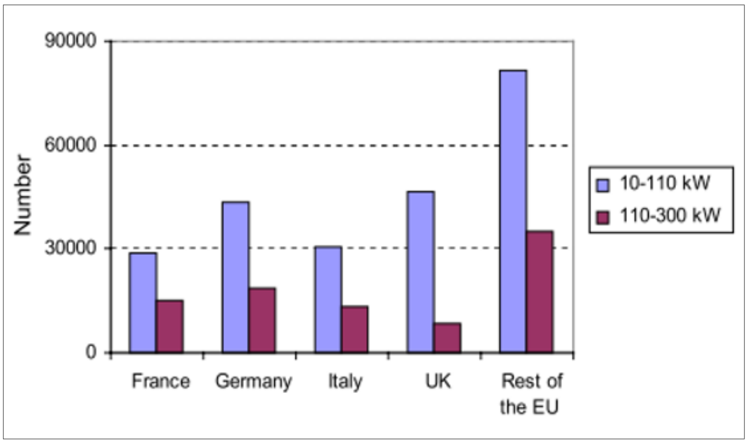

Figure 6 - Number of compressors by power range in the EU (Radgen & Blaustein, 2001)

Figure 6 above shows the number of compressors by power range in some European countries (Radgen & Blaustein 2001). It is estimated that there are more than 320.000 air compressors within the 10-300 KW power range installed in the European industries, about 70 percent of them are within the lower 10-110 KW range. Looking at the Italian context, the study estimates almost 31.000 compressors in the 10-110 kW range and more than 13.000 units in the range 110-300 kW. However, numbers become tremendously larger if lower power compressors are included in the statistics. To give an idea of the order of magnitude, it has been estimated that the oil-injected rotary compressors (with power higher than 2 KW) installed in Italy in 2009 were more than 200.000 units (Anglani & Mura 2010).

2. SIGNIFICANT SHARE OF ELECTRICITY USE

Compressed air production is an energy intensive process. Generation of compressed air accounts for as much as 10 percent of the EU industrial consumption of electricity. Estimates indicate that EU air compressors consume over 80 TWh of electricity, and produce 55 million tons of CO_2 per year (Radgen & Blaustein 2001). Figure 7 shows compressed air energy use in the European countries: Germany, Italy, France, and Great Britain together account for 60 percent of the entire European use of compressed air. Data from the rest of the world are in line with the European ones. For example, in China air compressors use 9,4 percent of China's industrial electricity, in the US they account for about 10 percent of total industrial energy use, and in South Africa about 9 percent (Saidur et al. 2010).

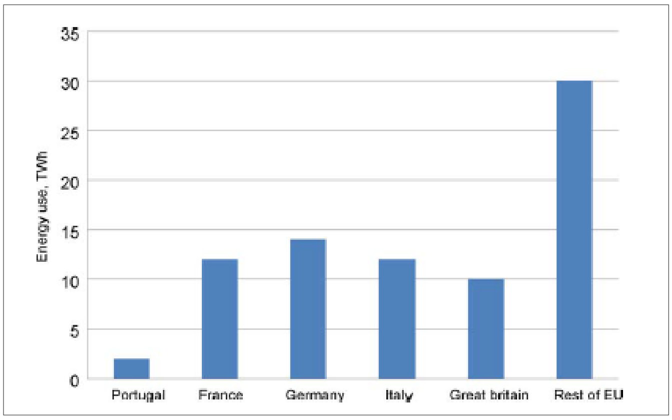

Figure 7 - Compressed air use in the EU (Radgen&Blaustein, 2001)

Compressed air usage in not homogeneous in the industry. Some sectors make greater use of compressed air, hence the share of compressed air in the electricity bill of these industries is larger. Table 1 shows the percentage of the electricity consumed by air compressors with respect to the total electricity consumed by motor systems in different industrial sectors in the United States. Notably, compressed air systems account for 28 percent of electric motor system consumption in the chemical branch, versus 16 percent of an average manufacturing facility.

SIC CODE	MANUFACTURING SECTOR	% COMPRESSOR CONSUMPTION
20	Food and Kindred Products	7,7%
26	Paper and Allied Products	4,6%
28	Chemicals and Allied Products	27,7%
29	Petroleum and Coal Products	15,3%
33	Primary Metal Industries	14,3%
-	Other	15,0%
-	Average in manufacturing	15,8%

Table 1 - Share of compressed air in the total consumption of electric motors by industrial sector (United States Department of Energy, 2002)

3. LARGE ENERGY SAVING POTENTIAL

From the perspective of industrial decision makers, energy consumption should be a concern, as compressed air is probably the most expensive form of energy available in a plant. Considering the total life cycle costs (LCC), the initial investment and the maintenance represent only a small portion of the overall cost. The power required to run the compressor, instead, is typically about two thirds or more of the total cost (Figure 8).

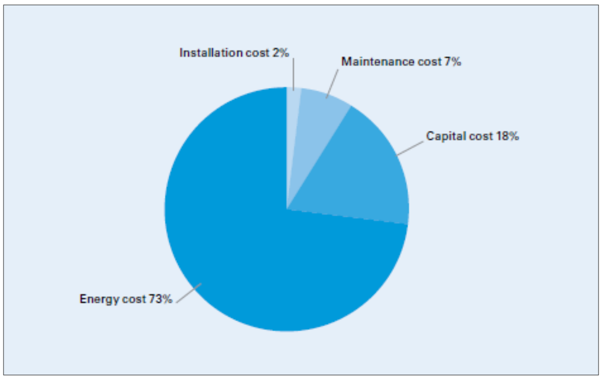

Figure 8 - Compressor costs over a ten-year lifecycle (Carbon Trust, 2012)

Although the weight of the different types of costs depends on several factors (e.g. type and power of the compressor, number of operating hours per year, auxiliary equipment included in the calculation), energy costs will always take the lion share of the overall cost of compressed air. This just goes to show that, when planning a new investment, it is best to look at the entire life-cycle of the plant, rather than making decisions based on its initial cost. It is worth remembering that maintenance, which accounts for only 7 percent of the total costs, is a crucial activity for maximising the energy efficiency of the air system.

There are countless opportunities to improve the energy efficiency in compressed air systems. In most cases, these opportunities are not only technically, yet also economically feasible. In fact, the high energy consumption makes adoption of energy efficiency interventions quite interesting investments from an economic standpoint. In many cases, EEMs secure large yearly savings that allow to recover the initial investment in a relatively short time, and continue to save operating costs year after year (Saidur et al. 2010).

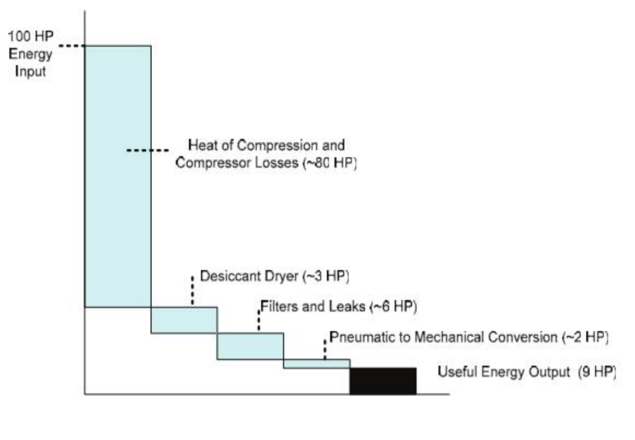

Figure 9 - Energy losses in a compressed air system (CEATI, 2007)

As an example, the recovery of the heat dissipated by the compressor is a higly recommended intervention. In fact, no more than 20 percent of the energy absorbed by a compressor can be converted into compressed air. The remaining 80 percent is lost as waste heat, most of which can be cost-effectively recovered and used for process applications, space or water heating. In reality, 20 percent is an optimistic estimate because other system losses are not taken into account. In fact, even in the most efficient system, piping and equipment will inevitably lead to pressure drops. Figure 9 illustrates the typical losses associated with production, treatment, and distribution of compressed air. As a rule of thumb, as little as 10 percent of the total energy supplied to the compressor is available as usable work at the point of use (Carbon Trust 2012). Replacing filters and fixing leaks are just two examples of inexpensive and simple practices that allow to reduce the energy waste throughout the system.

Despite several opportunities to save energy exist, evidence shows that the actual energy efficiency level of industrial compressed air systems is much lower than its economic potential. The Motor Challenge Program (US Department of Energy) analysed the market of industrial electric motors systems in the US, combining primary data with the results from the assessments of 265 industrial facilities. Regarding compressed air, it concluded that the unexploited energy efficiency potential is around 17 percent, achievable by means of both system improvements (14,5 percent) and variable speed controls (2,5 percent). This value does not include the potential saving resulting from motor improvements, that would lead to a further energy reduction of 4,3 percent. (United States Department of Energy 2002).

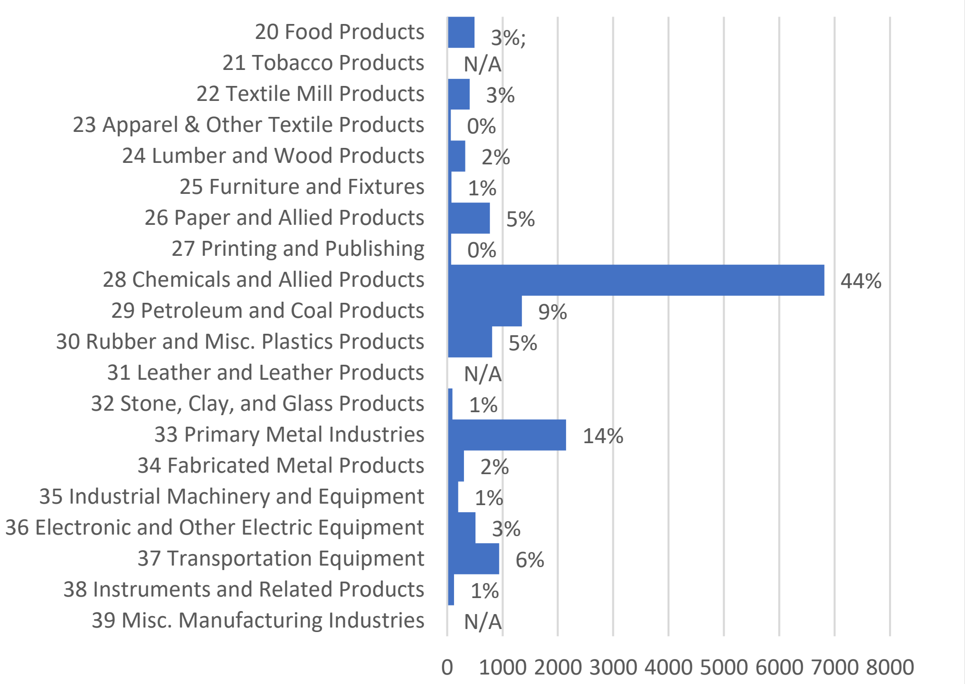

Table 2 - Energy saving potential in the compressed air by sector [GWh/year] (United States Department of Energy, 2002)

According to the study, the full exploitation of the energy efficiency potential would save about 10 to 20 TWh of electricity per year. The contribution of different manufacturing sectors to the total potential is shown in Table 2. As it can be seen, chemical companies hide the largest share (44 percent). Following, we find other energy intensive sectors, such primary metals (foundries) and petroleum and coal manufacturers, representing 14 and 9 percent of the saving potential respectively.

In 2001, a study carried out with the support of the European Commission under the SAVE Program analysed the energy consumption and the saving potential of the compressed air systems in the European industry. It determined that the energy saving potential resulting from the implementation of cost-effective measures is about 33 percent of the current energy consumption (Radgen & Blaustein 2001). In other words, one third of the energy currently consumed in the industrial compressed air systems could be cost-effectively saved.

Table 3 reports several other estimates of the energy efficiency gap, stemming from both case studies and practitioners' experience. Although estimates are somewhat varying, the main conclusion that can be drawn is that there is a big room for improving the level of energy efficiency in the compressed air plants.

(Hongbo & McKane 2008) report the results of over fifty compressed air energy audits conducted by the Shanghai Energy Conservation Service Centre. Results provide evidence that the energy savings potential in the assessed plants is between 10 and 50 percent.
Work conducted by the Energy Research Group at the University of Waikato (New Zealand) demonstrated energy savings of 20 – 30 percent in the compressed air systems in food, plastics, and wood processing industries (Neale et al., 2006).
Comprehensive energy audits carried out by the Irish Energy Centre revealed energy saving potentials of 41 and 49 percent in the compressed air plants of two food factories in Ireland (Irish Energy Centre 2006).
Many systems waste around 30 percent of the compressed air through leaks, poor maintenance, misapplication and poor control (Carbon Trust 2012).
According to Quincy (one of the word leading compressor manufacturers), there is typically a 20 to 30 percent savings opportunity in most facilities with a power of 35 KW or more (Quincy Compressor 2012).
According to Air Technology (an organisation specialised in optimising compressed air, gas and water systems), the average energy saving potential in a compressed air system is about 30 percent (Air Technology Ltd 2007).

Table 3 - Energy efficiency gap in industrial compressed air systems

1.5 Purpose of the study

The brief introduction outlined in the previous sections was intended to show the relevance of the research topic. The ever-increasing global energy demand, the uncertainty of fossil fuels supply and the environmental issues related to their combustion make energy efficiency a topic of utmost importance. The industrial sector with its large share of energy use can play a crucial role to achieve the targets set by policy makers. Particular attention should be devoted to SMEs, which largely dominate the manufacturing scenario and several studies show to be the most inefficient companies. Besides firm dimension, studies suggest that other firms' characteristics can affect the shape of the energy efficiency gap (e.g., (Cagno & Trianni 2014) and (Backlund, Broberg, et al. 2012)).

Going down at technology level, the generation of compressed air can be one of the more energy consumptive activities taking place in an industrial plant. Energy costs represent the largest share of the life-cycle-cost of a compressed air system. Then, it is in the public and private interest that compressed air is generated and used as efficiently as possible. Nevertheless, several studies agree that the energy efficiency potential is far from being fully exploited. Bearing these considerations in mind,

The present dissertation will focus on the adoption of energy efficiency measures (EEMs) in the industrial compressed air systems within manufacturing SMEs with the following objectives:

- ✓ **R.O. 1: INVESTIGATE THE LEVEL OF IMPLEMENTATION of selected air compressed EEMs considering both the characteristics of the EEMs and some relevant company characteristics; and**
- ✓ **R.O. 2: INVESTIGATE BARRIERS and DRIVERS to the ADOPTION of selected air compressed EEMs considering some relevant company characteristics.**

The interventions' characteristics that will be analysed are:

- Type of intervention; and
- Portion of the compressed air plant targeted by the intervention.

The firms' characteristics that will be analysed are:

- Size;
- Sector; and
- Energy Intensity.

Two methodologies will be followed to achieve the stated goals: the analysis of the U.S. database developed under the Industrial Assessment Centres (IAC) Program, and an exploratory investigation among SMEs in Lombardy.

The remainder of the thesis is structured as follows. First, to establish an adequate technical frame of reference, Chapter 2 will be devoted to the description of the main sub-systems and components of a typical industrial compressed air installation. Building from these basic engineering notions, Chapter 3 will present the selected EEMs that the IAC recommends for enhancing the energy efficiency of the compressed air systems. Chapter 4 will start addressing the R.O. 1, by presenting the main results of several descriptive analyses of the IAC database. Chapter 5 will provide the theoretical background on the barriers and drivers to energy efficiency, including a presentation of the taxonomies that will be used in the survey. Chapters 5 is the main thrust of this study: it will finalise the two R.O.s discussing the findings from the explorative investigation among Italian SMEs on the implementation of EEMs, and the barriers and drivers to their adoption. Finally, Chapter 6 will draw the summary conclusions of my thesis.

CHAPTER 2 - INDUSTRIAL COMPRESSED AIR SYSTEMS

This chapter is dedicated to the description of a typical industrial compressed air system, with an attention to the energy relationships existing among the various subsystems and components. The chapter is structured as follows: paragraph 2.1 will first provide an overview of the industrial compressed air systems; section 2.2 will deal with the equipment related to the generation of the compressed air; paragraph 2.3 will describe the various air conditioning equipment; section 2.4 will be devoted to the distribution network; finally, section 2.5 will focus on some end-uses of the compressed air.

2.1 Generic system description

Industrial compressed air systems are normally quite complex, consisting of several machines feeding a pipe system which runs throughout the factory to the end-use equipment. Figure below shows the typical components and how they could be arranged.

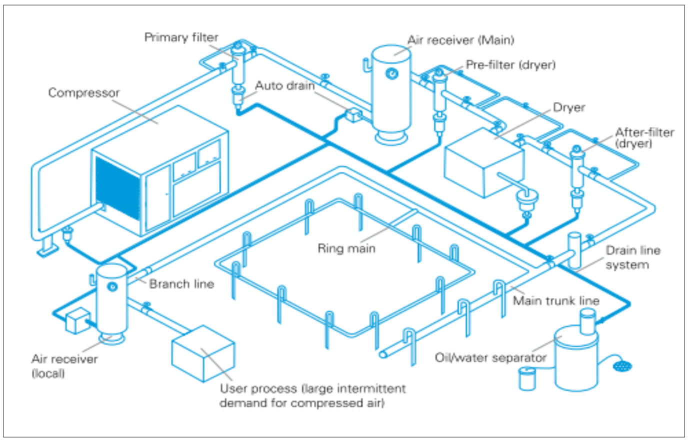

Figure 10 - A typical compressed air system (Carbon Trust 2012)

After passing through an inlet filter, atmospheric air is drawn into the compressor, where it is pressurised to the required level. An AC electric motor usually powers the compressor, eventually regulated by the most adequate type of control to match the air supply with the demand. A cooling system is always included to remove the huge amount of heat generated during the compression process. Many modern industrial air compressors are sold packaged in a box frame, on which the compressor and accessories are mounted, allowing for a significantly simplified installation. The complete compressor package is often enclosed in a sound and vibration reducing enclosure (Atlas Copco 2015).

After exiting the compressor, the air flows through a series of conditioning equipment. The quantity and type of equipment, as well as the way they are set up can be very different. In general, a system includes a primary air receiver, one or more compressed air filters, and a dryer. The air tank acts as a reservoir to store the compressed air and to ensure that the system can cope with variations in demand reducing the burden on the control system. The air treatment equipment (filters and dryers) remove impurities such as dirt, water, and oil added by the compressor. Some types of dryers require filtration both upstream and downstream. Properly positioned traps allow to collect the condensate formed from the moisture due to a decrease of the air temperature and/or an increase of pressure. If an oil-injected compressor is used, the water/oil mix must be properly treated.

The compressed air is then led to the various uses through a distribution network, whose layout can be relatively straightforward or very complex. The best solution consists of designing a pipe system with a closed loop ring around the area in which air consumption occurs. Branch and drops lines are then run from the main ring to the various consumer points. This provides uniform compressed air supply despite heavy intermittent usage, as the air is fed to the points of consumption from two directions. This system should be used for all installations, except if a compressed air user of large air consumption is located at a great distance from the rest of the equipment (Talbott 1992). As shown in Figure 10, in this case it is better to use a separate line to serve this type of user. Strategically locating secondary air receivers near sources of high and/or intermittent demand can also be effective. Valves should be properly positioned all over the system to regulate, deviate, or block the air flow as needed. At the points of end use, air pressure is often lowered with pressure regulators, which may be coupled with lubricators and a further filter.

Of course, not every compressed air installations need all the equipment and components mentioned above. Furthermore, several ways exist to compress air, condition it, and distribute it to the end points of use. Therefore, there is no such a thing as a standard compressed air system (Talbott 1992). In general, it is good industrial practice to install the compressor and the other major equipment (such as motor, primary receiver, and dryer) in a dedicated room, commonly referred to as compressor room. This can be either an external plant, or a separate area within the building. When selecting the compressor room location, several constraints and considerations must be carefully weighted, such as:

- disturbance of working activity due to compressor noise;
- availability of solid, flat, and anti-vibration foundation;
- hazardous situations and risks for the workers;
- proper ventilation and availability of coolant;
- possibility to draw clean, dry, and cool air from outside the building;
- accessibility for operation and maintenance;
- risk of freezing of the condensate in outdoor pipelines;
- future expansion needs; and
- facilitation of heat recovery.

From an energy efficiency perspective, system's layout is a significant factor. Even more importantly, it is complex and expansive to modify it once the system is built. Work stations and/or compressors locations may be selected to minimise the length of the distribution lines, in order to reduce frictional losses (Zahlan & Asfour 2015). It may be convenient to locate the compressor nearby a central position and possibly close to the large compressed air users. The number of valves, bends, transitions, fittings, and any flow obstructions should be minimised to avoid excessive concentrated pressure drops.

System specification is the basis for overall system design and components selection. It consists of a careful definition of the air flow, pressure and quality at all critical points in the system. Measurement or estimation of the operating data for the equipment to be supplied is the first step of this process, which extents back through the distribution system, conditioning equipment and compressor (Talbott 1992).

The required system capacity depends on the air consumption of all the connected tools, machines, and processes, and on their individual utilization factors. The total nominal air requirement is not the sum of the maximum requirements, but the sum of the average air consumption of each user

(Lawrence Berkeley National Laboratory 2003). Compressor capacity is essentially determined by the total nominal compressed air requirement. Systems additions for leakage and wear must be taken into consideration from the beginning. Approximations of the calculations, as well as potential growth of air demand should be also taken into account. Nevertheless, it must be reminded that an oversized compressor is an inefficient compressor. Storage tanks should be adequately sized and positioned to dampen demand fluctuations and meet high short-term loads. Often, an appropriate type of control system is suitable to better follow the demand profile.

Normally, different types of equipment require different pressures within the same plant. Pneumatic tools manufacturers rate tools for specific pressures, while process operation pressure requirements should be specified by process engineers. The highest pressure determines the required system pressure and the other equipment will be fitted with pressure regulators at the points of consumption. In some cases, this method can waste a lot of energy. Consideration should be given to adopt separate distribution systems and compressors, or to install boosters close to the high-pressure applications (Talbott 1992). The compressor discharge pressure is determined by adding to the working pressure all the distributed losses that occur along the network and the concentrated ones at the various equipment (e.g. aftercooler, dryer, filters, and separators).

Quality is determined by the dryness and contaminant level required by the end uses, and is accomplished with filtering and drying equipment. Higher quality air usually requires additional equipment, which not only increases the initial capital expenditure, but also makes the overall system more expensive to operate in terms of energy and maintenance. One of the main factors in determining air quality is whether lubricant-free air is required. Lubricant-free air can be produced with either oil-free compressors, or with lubricant-injected compressors that have additional separation and filtration equipment. If quality requirements are not equal throughout the plant, then it should be assessed the possibility of adding localised treatment only for the special operations.

At this point, it is important to remark that an air system cannot be treated as a mere assembly of components. In fact, virtually all pneumatic devices behave one way when they are isolated from the compressed air system, and they behave differently when they are part of the dynamic system (Perry & Minette 1998). Thus, correct design, but also operation and maintenance, should adopt a system approach, which considers the interactions among the different elements. In the following of the chapter, the machines, equipment, and components mentioned in this introductory section will be individually described. To do so, it is useful to schematize a compressed air system using a simplified block diagram, as the one shown in Figure 11 (Belforte 2005). A generic compressed air system can be then broken down into four main subsystems, such as:

- Compressed air generation (1). It includes the air compressor and related cooling system, the motor drive, and the control system.
- Compressed air conditioning (2). It typically consists of an air receiver, an air dryer, and various filters.
- Compressed air distribution and ancillary equipment (D). This includes piping and connectors, traps and other valving, and pressure regulators.
- Compressed air use (U). It refers to the various workstations where are located the pneumatic tools and equipment.

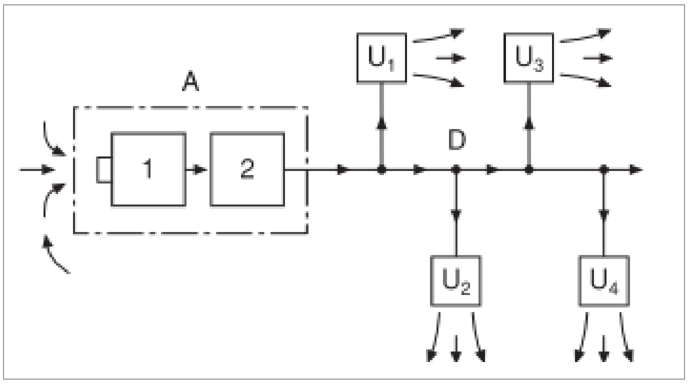

Figure 11 - Block diagram of an industrial compressed air system (G Belforte, 2005)

2.2 Generation equipment

2.2.1 Air compressor

A compressor is a machine that takes in air or any other gas at low (typically atmospheric) pressure and compresses it to higher pressure. It is a power consuming machine, in which the shaft power is converted into pressure energy of the working fluid. The compression cycle can be examined with reference to the conventional single-acting reciprocating compressor, schematised in Figure 12 in the next page (Belforte 2005). The piston (1) moves forward and backward within the cylinder, and it is coupled through a hinge (2) to the connecting rod (3), which in turn is powered by a rotating crankshaft. Element (4) is a counterweight that partially balances the mechanical loads, whereas in the upper part of the cylinder are located a suction valve (V_A) and a discharge valve (V_S). They are both one-way valves, namely the suction valve will only let air come into the compression chamber, whereas the discharge valve will only let air out. The displacement of the piston, with the proper phasing of the opening and closing of the valves, results in the thermodynamic cycle of the gas.

Figure 12 (a) shows the ideal compression cycle on the pressure-volume plane. Considering the top dead end as initial position of the piston, the four transformations undergone by the gas are: suction, compression, discharge, and pressure reduction.

- Suction (1-2). The piston moves downward through the cylinder, the suction valve is open, the discharge valve is closed. A volume of air V2 is drawn into the compression chamber at pressure P1. At end of the stroke, the piston is positioned in the lower dead point.
- Compression (2-3). The piston moves upward through the cylinder, the suction and the discharge valves are closed. As the space available to the air enclosed in the chamber reduces, its pressure increases until reaches the designed built-in pressure value of the discharge valve P3. In an ideal machine, the compression process occurs at constant temperature, which requires the minimum amount of work.
- Discharge (3-4). The piston moves upward through the cylinder, the suction valve is closed, the discharge valve is open. Air is pushed out through the discharge valve by the piston. At end of the stroke, the piston is positioned in the upper dead point.
- Pressure reduction (4-1). The piston is still in the upper dead end, the inlet valve opens, and the discharge valves closes. In an ideal compressor, the pressure instantaneously drops without any piston movements.

The work necessary to compress the air volume V2 is graphically represented by the area 1-2-3-4 on the p/V diagram. This very ideal cycle assumes that the piston can reach the upper dead end with zero volume of air left in the cylinder. In reality, a clearance volume V0 underneath the inlet and outlet valves and above the piston must always remain for mechanical reasons (Atlas Copco 2015). Hence, before suction can start, the air remained in the clearance volume after the closure of the discharge valve must expand to reach the pressure P1. Such expansion reduces the volume of air that can be drawn during the suction stroke of a quantity V1.

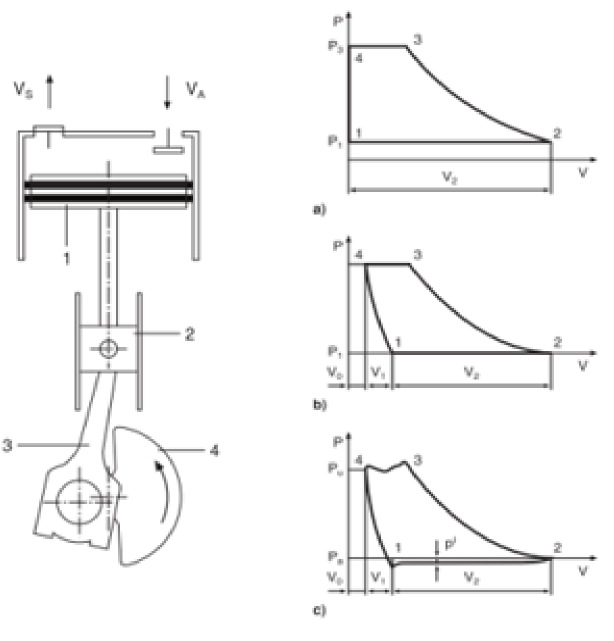

Figure 12 - Single-acting reciprocating compressor (on the left); Compression cycle (on the right): ideal (a), ideal with clearance (b), real (c) (G Belforte, 2005)

The difference between the theoretical p/V diagrams (a and b) and the actual diagram (c) is due to the practical design of a compressor. The valves are never completely sealed and there is always some leakage between the piston and the cylinder wall. In addition, the valves open and close with some unavoidable delay, which causes a pressure drop when the gas flows through the channels. Furthermore, the gas is always heated when flowing into the cylinder, which results in an isentropic (at constant entropy) rather than isothermal (at constant temperature) compression. These elements all lead to a higher specific compression work (Atlas Copco 2015).

In theory, if the compressed air could be used immediately at its final temperature after compression, the isentropic compression process would have some advantages. As the air is rarely used directly after compression, and is usually cooled to ambient temperature before use, an isothermal compression process is preferable as it requires less work. Because realising a perfect isothermal compression is unpractical, a common method to approach it involves dividing the compression into several stages, and cooling the air after each stage (Belforte 2005). This increases the energy efficiency, with the best result being obtained when each compression stage has the same pressure ratio[3].

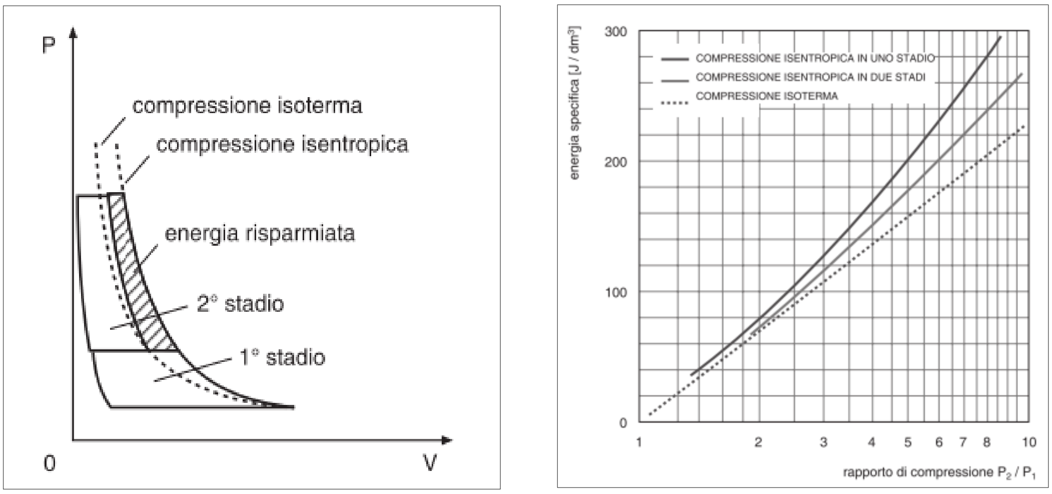

Figure 13 – (a) left and (b) right: energy savings achievable with a two-stage compression cycle (G Belforte, 2005)

As shown in Figure 13 (a), the air is compressed in a first compression step, then cooled in an inter-cooler, and hence compressed again in a second compression stage. In this way, the final temperature is higher than the one of an isothermal process, but lower than the one of a single-stage isentropic compression. The dashed area represents the energy savings achieved thanks to the two-stage cycle. By increasing the number of compression stages, the entire process better approximates an isothermal compression, thus increasing the energy efficiency. However, the number of stages of a real compressor is limited by both economic and constructive factors.

---

[3] Pressure is intended as absolute (a) when measured from a baseline of a perfect vacuum, and relative (or gauge) (g) when measured from a baseline of atmospheric pressure. Hence, Absolute pressure = Gauge pressure + Atmospheric pressure. The pressure ratio is the ratio between the absolute pressure on the outlet and on the inlet sides. Unless specified, the pressure values reported are to be intended as absolute.

One-stage compressors are normally employed for pressures up to 6 bar, both one- and two-stage units can be specified in the range 6-12 bar, whereas two-stage compressors are strongly recommendable for higher pressures up to 30 bar (Belforte 2005). Figure 13 (b) shows the theoretical specific compression energy in function of the logarithm of the pressure ratio, for an isothermal (dashed line), an isentropic one-stage (solid dark line), and an isentropic two-stage (solid transparent line) process. As it can be seen, the higher the pressure ratio, the higher the energy savings achievable with a two-stage compression. To obtain the real compression energy, the mechanical and electrical performances of the machines must be taken into account.

There are two generic principles for the compression of air (or gas):

- positive displacement; and
- dynamic.

A positive displacement compressor relies on the physical principle that a change in the volume of a gas results in a pressure (and temperature) variation. A displacement compressor increases the pressure of a captured pocket of air by physically reducing its volume through the displacement of one or more moving members. A dynamic compressor, instead, uses a rotating element (the impeller) to increase the velocity of a continuously flowing gas stream, and that is converted to static pressure by then slowing the gas through a diffuser. In simple terms, air is accelerated first and then slowed down to convert its kinetic energy into static pressure (Atlas Copco 2015).

The performance characteristics of these two types of compressors are markedly different. A positive displacement compressor delivers an almost constant volume of air when operated at fixed speed, while the system load condition determines the discharge pressure. In a dynamic compressor, instead, the volumetric flow rate varies inversely with the differential pressure across the compressor.

Figure 14 shows the full range of compressors, classified according to their working principle. Positive displacement compressors break down into two main categories, according to the type of mechanical element used to compress the air: reciprocating, which use pistons, and rotary, which use rotating parts. Reciprocating compressors can be further split into single-acting and double-acting. Rotary compressors, instead, can be helical-screw, liquid-ring, scroll, sliding-vane, or lobe. Dynamic compressors can be distinguished into centrifugal and axial, depending on the flow pattern: in a centrifugal machine it is radial, in an axial one it is co-axial with the shaft. Although all these types of compressors are currently available, four types of machines dominate the market for manufacturing applications: reciprocating (single-acting and double-acting), rotary helical-screw, and centrifugal.

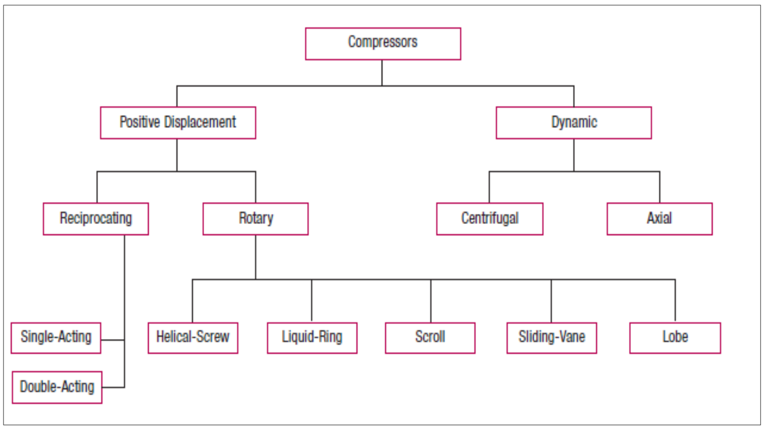

Figure 14 - Compressors family tree (Lawrence Berkeley National Laboratory, 2003)

The selection of the most adequate type of compressor is firstly driven by the air flow and pressure requirements. Although there is a large overlapping of the working conditions for the different compressors, some general guidelines apply. Large double-acting reciprocating units are the main machine used for low-flow and high-pressure applications from 30 to 400 bar. On the other hand, centrifugal compressors are the technology of choice for high flow rates, especially above 60 m^3/min, when they typically become more efficient than rotary screw units. Air screw compressor is the most common type in the manufacturing air plants operating at pressures of 6 – 11 bar (Carbon Trust 2012).

Another feature which is worth carefully analysing when selecting the compressor is the quality of the air delivered. In this regard, compressors can be distinguished into two categories:

- oil-lubricated; and
- oil-free.

Reciprocating and rotary screw compressors are available in the two designs, while centrifugal units are inherently oil-free. When used, lubricant performs several functions: it acts as a seal between the moving elements and the cylinder, reduces the friction between the mechanical components, minimises wear and other damages, absorbs most of the heat of compression, lowers the operating temperature, and extends the life of the compressor. Lubricant may be supplied by simple flooding of a moving element in an oil reservoir or by using a pumping and injection system. Either way, the lubricant enters the compression chamber, so that the air at the compressor outlet is contaminated with oil, both in liquid and aerosol form. Hence, adequate treatment equipment must be installed downstream the compressor. This equipment not only represents an additional upfront cost, but also causes extra energy losses. Nevertheless, the quality of the properly treated air can be considered more than adequate for the majority of manufacturing uses.

However, some applications in industries such as food and pharma require air to be perfectly clean, penalty being huge costs associated with product contamination. To avoid this risk, it is recommendable to use oil-free compressors, which do not allow lubricant in the compression chamber. On the other hand, it must be considered that lubricant-free rotary screw and reciprocating compressors usually have higher first costs, lower energy efficiency, and higher maintenance requirements than lubricant-injected versions. Thus, when air quality requirements can be met either by an oil-free unit, or by an oil-lubricated compressor equipped with proper separation and filtering, the optimal choice should be carried out comparing the differential costs of the two options (Atlas Copco 2015).

In general, when more than one type of compressor meets flow, pressure, and quality constraints, the selection process should include several quantitative and qualitative aspects, such as:

- life-cycle cost;
- energy efficiency;
- compactness;
- easiness of installation;
- noise and vibration level;
- performance over time;
- maintenance requirements; and
- controllability.

In the remaining of the section, the four types of compressors most commonly installed at manufacturing facilities are briefly described.

RECIPROCATING COMPRESSOR

Reciprocating compressors (also referred to as piston compressors) use a piston-cylinder arrangement, where the displacement of the piston in the cylinder causes a pressure rise of the trapped air. They are called “reciprocating” because the piston goes back and forth in a reciprocal motion. Basically, reciprocating compressors use the same working principle of a car engine, but in reverse: in a car engine, the combustion of the gas in the chamber powers the piston, whereas in a compressor it is the piston that pushes the gas. More precisely, the rotation of the compressor's crankshaft is converted into an axial displacement of the piston by means of a rod connection; the piston displacement causes a variation of the volume available for the air in the compression chamber, and hence of its pressure; the suction and discharge valves control the flow of air through the cylinder. An unavoidable consequence of the alternating motion of the piston is the intermittent supply of compressed air, which leads to air pressure fluctuations. For this reason, this type of compressor should be coupled with an air receiver which dampens the pulsating effect. Depending on the number of active strokes per cycle, reciprocating compressors are distinguished into:

- single-acting; and
- double-acting.

Single-acting reciprocating compressor

A single-acting unit performs the compression on one side of the piston, thus there is only one compression stroke per cycle. As stated above, single-acting piston compressors can be designed oil-lubricated or oil-free. An oil lubricated model may utilise a splash or a full pressure lubrication system. With the former design, a dipper mounted on the connecting rod dips into an oil reservoir in the crankcase each revolution and produces an oil splash which lubricates the connecting rod, piston pin, main bearings, and cylinder. In the pressure lubrication (also called oil injected) design, instead, a positive displacement oil pump draws the oil from the reservoir in the crankcase and feeds it through the drilled passages in the crankshaft and connecting rod to the crank pin and the piston pin (CAGI 1998). On the other hand, an oil-free compressor (also called non-lube) does not allow oil in the compression chamber, and uses pistons and piston rings that are self-lubricating or heat resistant guides.

Single-acting reciprocating compressors can pressurise the air in a single or in multiple steps. Single-stage units are usually rated at discharge pressures from 2,5 to 10 bar, two-stage from 10 to 13 bar, and multi-stage for pressures above 13 bar. Two-stage and multi-stage designs often include inter-stage cooling to reduce discharge air temperatures for improved energy efficiency and durability.

The number of cylinders adopted depends on the air capacity required and the number of stages of compression. The number of cylinders does not define the number of stages, and the number of cylinders must be equal or greater than the number of stages. For example, a two-cylinder compressor will compress air in one stage if the two elements work in parallel to supply higher air flow rate. A variety of cylinders arrangements can be then used, such as: single vertical cylinder, in-line or side by side vertical cylinders, horizontal and balance opposed cylinders, V or Y configuration, W configuration. Figure 15 shows a single-acting reciprocating compressor consisting of three oil-splash lubricated cylinders.

Smaller models of single-acting compressors are the most common. These are relatively light, and often suitable for portable use, so that they can be located close to point-of-use. Typically, small units are directly mounted on an air receiver, which functions as a support frame (Figure 16). Although simple to maintain, single-acting compressors present several drawbacks, such as low duty cycles (often not more than 50 percent), relatively high noise, and energy inefficiency (Lawrence Berkeley National Laboratory 2003).

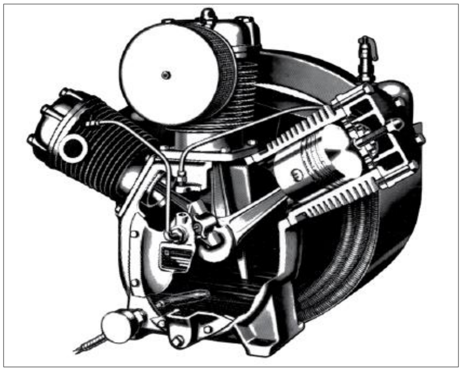

Figure 15 - Splash-fed single-acting compressor (CAGI, 1998)

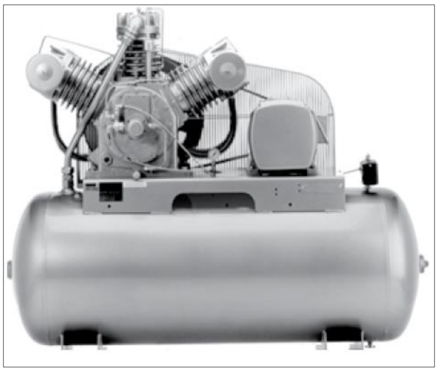

Figure 16 - Packaged single-acting compressor (CAGI, 1998)

Double-acting reciprocating compressor

A double-acting piston compressor uses both sides of the piston to compress the air, hence it realises two discharge strokes for every turn of the crankshaft. A piston rod is attached to the piston at one end and to a crosshead at the other end. The crosshead ensures that the piston travels concentrically within the cylinder. Compression chambers are positioned on both sides of the piston, and each chamber has its own suction and discharge valves. The basic design of a double-acting compressor includes oil-lubrication, single-stage compression, and a single cylinder. Starting from this design, several solutions can be obtained combining:

- oil lubrication or oil-free;
- single-stage, two-stage, or multi-stage compression;
- different cylinders configurations.

The lubrication system may employ a splash solution, a forced-fed one, or a combination of these two. In the majority of oil-free compressors, the piston moves in the cylinder bore on a synthetic or carbon wearing ring (Figure 17). Some design provide a distance piece between the crankcase and the cylinder to ensure that no part of the piston rod that enters the lubricated crankcase can reach the oil-free cylinder area.

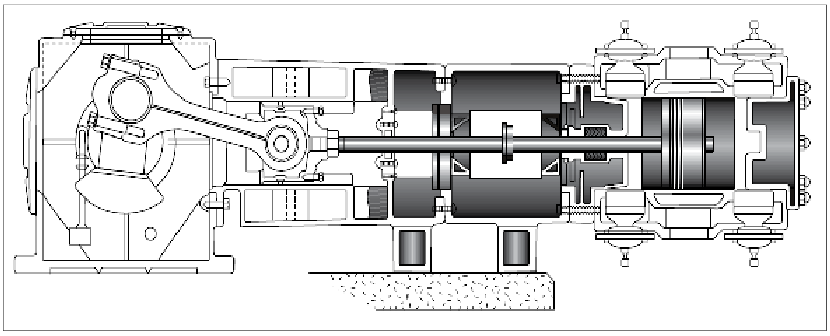

Figure 17 - Non-lubricated double-acting compressor (CAGI, 1998)

Multi-stage versions of heavy duty industrial double-acting compressors are often considered to be the most efficient units. However, several drawbacks are gradually leading to a reduction of their use. In fact, they have high initial and maintenance costs. Also, they are noisy and generate a considerable amount of vibration, thus require substantial foundations and high associated costs. Today, double-acting two-stage reciprocating compressors remain very common for high pressure applications, typically from 30 to 400 bar (Carbon Trust 2012).

Rotary helical screw compressor

Figure 18 in the next page shows the scheme of a rotary helical screw compressor (Belforte 2005). The machine consists of two intermeshing and counter-rotating rotors (1 and 2) located in a stator housing having an inlet port (I) at one end and a discharge port (U) at the other. The male rotor (1) has lobes formed helically along its length, while the female rotor (2) has corresponding helical grooves (flutes). The length and the pitch of the screw elements, as well as the form of the discharge port, define the build-in pressure ratio of the compressor. The female rotor is powered by the motor shaft (10) through a connector (9), while the male one is put in rotation by the external timing gears (7 and 8). The rotors do not come into contact with each other, nor with the compressor housing. The synchronising gears allow to maintain tight clearances between lobes and grooves, and lobes and housing. The shafts are supported by four bearings (3, 4, 5, and 6). The bearings (3 and 4) must be able to overcome the axial force generated by the pressure difference between the inlet and the outlet.

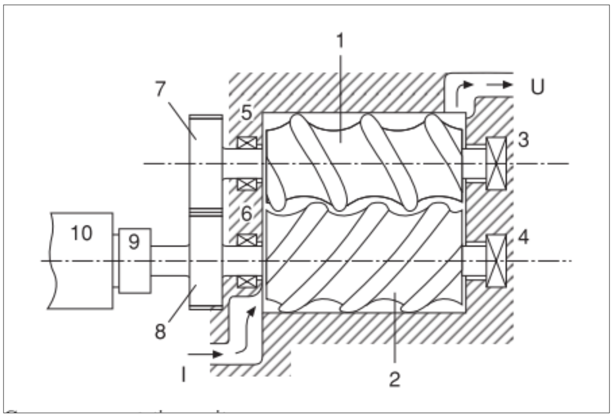

Figure 18 - Rotary helical screw compressor (G Belforte, 2005)

As any other positive displacement unit, the compression principle of a rotary screw machine is based on the mechanical reduction of the air volume. The air flowing in through the inlet port fills the space between the rotors, realising a pocket of air between the lobe of the male rotor and the grove of the female one. As the screw elements rotate, they gradually enclose the space available to the air, resulting in increased pressure. Compression continues until the intermeshing pocket is exposed to the outlet port from where the compressed air is discharged.

The double helical screw units are available in oil-injected and oil-free designs. The oil-injected rotary screw compressor is the dominant type of industrial compressor for a wide range of applications. The generic term oil may refer to a hydrocarbon product but most compressors use cleaner and longer-life synthetic lubricants. The lubricant is injected into the compression chamber for three basic functions (CAGI 1998):

- it lubricates the intermeshing rotors and associated bearings;
- it removes most of the heat generated by the compression;
- it acts as a seal in the clearances between the rotors and between rotors and stator.

A mixture of compressed air and oil leaves the air end, requiring adequate treatment equipment to be installed downstream the compressor. Air is first passed to a sump/separator to separate most of the oil, either by gravity or by direction and velocity changes. The remaining aerosols in the compressed air then are separated by means of a coalescing filter, resulting in only a few parts per million (ppm) of oil carry-over (usually in the range 2 - 5 ppm). The oil removed from the air in the separator must go through a filter for cleaning and a heat exchanger for cooling, before being injected again into the compressor for a new cycle.

Oil-injected screw compressor elements can be manufactured for high pressure ratios, with one compression stage usually efficient for pressure up to 12 - 13 bar. Higher pressures up to 17 bar can be achieved, but at the expense of energy efficiency, so a two-stage design may be cost-effective. In the oil-free screw compressors the pressure ratio is limited by the higher temperature generated, and usually cannot be above 4 bar per compression stage. This is why oil-free screw compressors are frequently built with several stages and inter-cooling. The air flow that can be handled by a screw compressor is relatively large, typical upper values being 15 - 20 m^3/min (Belforte 2005).

Although the energy consumption is slightly larger than an equivalent double-acting reciprocating model, a screw compressor provides several advantages. It is generally not equipped with valves, and the absence of unbalanced mechanical forces allows to work at a high shaft speed, resulting in a large flow rate with small exterior dimensions. It has lower initial cost, as well as simpler installation and maintenance. Also, noise and vibration are significantly reduced, and the air is delivered uniformly, with minimum pressure pulsations. For all these reasons, rotary screw compressors are today used in most industrial plant air applications.

Centrifugal compressor

A centrifugal air compressor works a continuously flowing air stream which is radially discharged. The basic elements of a centrifugal unit are a rotating impeller and a stator housing. The impeller is mounted on the power shaft, and rotates at speeds commonly between 15.000 and 100.000 revolutions per minute (rpm). It is equipped with blades nearly radially oriented, and can have either an open or closed design (Atlas Copco 2015). The stator housing is the static element of the compressor, and it consists of a suction port, a volute, a diffuser, and a discharge port (Figure 19).

Being a dynamic machine, the compression principle is based upon acceleration and slow-down of the air. First, air is drawn into the centre of the impeller, which imparts a velocity to the air. This is progressively pushed out towards the perimeter of the impeller by the centrifugal forces. The radial movement results simultaneously in a pressure rise and in a generation of kinetic energy. The diffuser, which surrounds the impeller, forces the air to expand and converts its kinetic energy into pressure. The volute further reduces the air velocity and converts more kinetic energy to static pressure energy. Compressed air can be then discharged out the compressor stage.

The performance of a dynamic compressor is affected by the external conditions. For example, a reduction of the inlet temperature results in an increase of the capacity. In addition, as system pressure decreases, the compressor's flow capacity increases. The steepness of the pressure head/capacity curve depends on the impeller blades design: the more they lean backwards from the true radial position, the steeper the curve. An important and potentially troublesome consequence is a phaenomenon known as surge (Talbott 1992). As compressed air demand is reduced, the system pressure rises until a critical point is reached. At this critical pressure, the discharge air flows back into the compressor, immediately reducing the discharge pressure, and inducing a repetition of the flow-back. If this is not interrupted, a harmonic loading cycle is generated which could result in excessive vibration and potential damage to the compressor. To avoid this occurrence, the control system either unloads the compressor or discharges the excess air to the atmosphere.

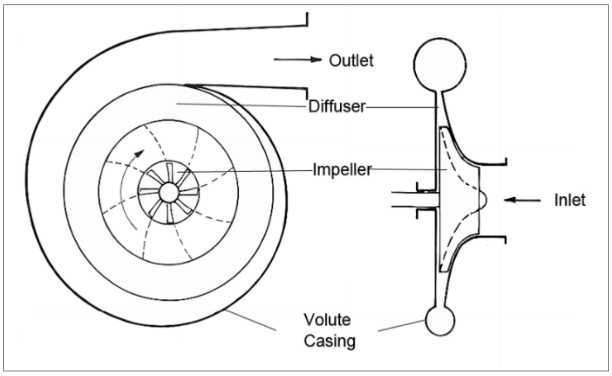

Figure 19 - Scheme of a centrifugal compressor

Centrifugal compressors have seen increasing usage for high volume plant air applications, also thanks to the delivery of oil-free air. The air flow rates generated can range from 10 to more than 3.000 m^3/min, but the more common centrifugal compressors are from 30 up to 150 m^3/min. They are best suited to applications where demand is relatively constant or where they can be used primarily for base-load operation, employing other compressor types as trim units to meet peak demands. The pressures required by industrial applications (6 – 11 bar) are normally achieved with two to four compression steps, often with inter-stage cooling.

2.2.2 Compressor drive

The prime mover is the main power source providing energy to drive the compressor. It must supply enough power to start the compressor, accelerate it to full speed, and keep the unit operating under various design conditions. Alternating current (AC) electric motors are by far the most common drivers used for industrial plant air compression. Large AC electric motors are available in two basic types:

- induction; and
- synchronous.

Induction motors are used in the majority of industrial applications, and are designed in two main styles: squirrel cage and wire wound rotor. Between these, the most common is the three-phase squirrel cage induction motor, which is used in all types of industries, as it is silent and reliable (Atlas Copco 2015). The electric motor consists of two main parts, a stationary stator, and a rotating rotor. On the one hand, the stator generates a rotating magnetic field and, on the other hand, the rotor converts this energy into movement, i.e. mechanical energy. The stator is connected to the three-phase mains supply. The current in the stator windings gives rise to a rotating magnetic field, which induces currents in the rotor and, in turn, this gives rise to another magnetic field, in the rotor. Basically, the interaction between the stator's and the rotor's magnetic fields results in a mechanical torque, which makes the rotor shaft rotate (Atlas Copco 2015).

In regard with the motor-compressor connection, this partially depends on the compressor type. Small reciprocating units are most often belt-driven. Larger reciprocating and rotary compressors are often flange connected. In multi-stage centrifugal compressors, a high-speed gearbox may be integrated with the compressor stages, to let the impellers rotate on high speed pinions. For example, Figure 20 shows a three-stage centrifugal compressor, where two speed-changing gears are used to increase the rotation velocity of the shaft.

It should be mentioned that other types of drivers besides electric motors can be used, although these are much less common. In principle, compressor power can be provided by any one of the following sources: electric motors, diesel or Otto-cycle engines, steam or gas turbines. For example, factories which are generating high pressure steam for other reasons may find it economic to operate steam turbine driven compressors, especially if the compressors are dynamic types. In other cases, large availability of natural gas could make gas-powered compressors economic (Talbott 1992).

A few final remarks on the energy efficiency of the compressor mover. In many cases, either a standard- or a premium-efficient motor can be specified when purchasing a compressor or replacement motor. The incremental cost of a premium efficient motor is typically recovered in a short time stemming from the resulting energy savings. When replacing a standard motor with a premium-efficient version, attention should be paid to performance parameters, such as full-load speed and torque. A replacement motor with performance as close as possible to the original motor should be used (Lawrence Berkeley National Laboratory 2003). Several other interventions, both hardware and operation/maintenance, can be undertaken to improve the efficiency of the motor. However, since electric motors are used in numerous industrial applications besides compressed air systems, the study of the energy efficiency of the compressor driver is out of the scope of this thesis.

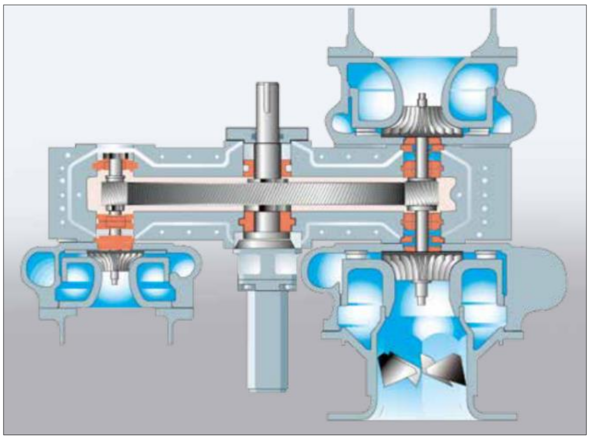

Figure 20 - Three-stage integral gear centrifugal compressor (Atlas Copco, 2015)

2.2.3 Compressor control

Compressed air systems are usually designed to operate within a fixed pressure range, and to deliver a volume of air that varies with the system demand. Compressed air system controls match the compressed air supply with system demand, although not always in real time. Basically, the control system decreases the compressor output when the pressure reaches an upper predetermined level, and increases it again when the pressure drops to a lower predetermined level. The difference between these two pressure levels is called the control range. Because few air systems operate at full-load all of the time, part-load performance is critical, and it is primarily influenced by compressor type and control strategy (Lawrence Berkeley National Laboratory 2003). In the following, the most common types of compressor controls will be discussed, distinguishing between individual and multiple compressor controls.

INDIVIDUAL COMPRESSOR CONTROL STRATEGIES

Various individual compressor control strategies exist, and the most appropriate one depends on the specific case. The main types of compressors' controls are: start/stop, load/unload, modulating control, variable displacement, and variable speed drive (VSD).

1. Start/Stop

This is the simplest control strategy that can be applied to either reciprocating or rotary screw compressors. Essentially, the motor driving the compressor is turned on or off in response to the discharge pressure of the machine. Typically, a simple pressure switch provides the motor start/stop signal (Figure 21). Start/Stop strategies are generally appropriate for relatively small compressors (in the range 2 - 7,5 KW) and with low-duty cycles (50 – 60 percent). It should not be used instead in applications that have frequent cycling, because repeated starts will cause the motor to overheat and other compressor components to require more frequent maintenance. Furthermore, a large system buffer volume or large pressure difference between the upper and lower limits are required to minimize the number of cycles. The advantage of this regulation method is that the power is used only while the compressor is running, hence it is energy-efficient and effective, provided that the number of starts is kept low (Atlas Copco 2015).

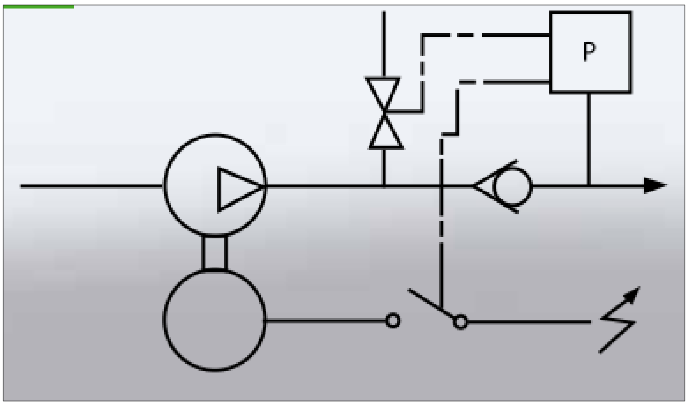

Figure 21 - Scheme of a compressor with start and stop control (Atlas Copco 2015)

2. Load/Unload

It is the most common regulation method used for compressors with power greater than 5 kW. Such control keeps the motor running continuously at constant speed, but unloads the compressor when the discharge pressure is adequate. With this control, the compressor's inlet valve is either fully opened (loaded) or fully closed (unloaded), while there is no intermediate position (Atlas Copco 2015). The figure below shows the pressure band (Min–Max) within which the compressor operates: when pressure reaches the lower threshold "Min" the compressor is loaded, whereas it is off-loaded at the pressure "Max". There are different strategies for unloading a compressor, but in most cases an unloaded rotary screw compressor consumes between 15 and 35 percent of full-load power, while supplying no useful work. As a result, some load/unload control schemes can be inefficient. Optional unload timers are available that save energy by automatically turning off the compressor if the unit runs unloaded for a certain period of time (e.g. 15 minutes). Load/unload control strategies require significant air storage receiver capacity for efficient part load operation and to obtain real savings in energy (CEATI 2007).

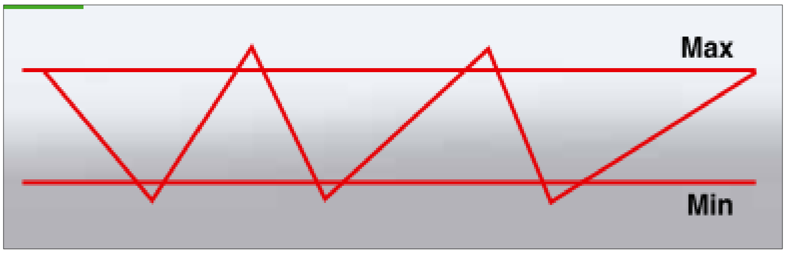

Figure 22 – Working principle of a Load/Unload compressor control (Atlas Copco 2015)

3. Modulating Control

This mode of control varies the compressor output to meet flow requirements by adjusting (throttling) the inlet valve, resulting in air restrictions to the compressor air inlet. It is applied to centrifugal and lubricant-injected rotary screw compressors, whereas it cannot be used on reciprocating or lubricant-free rotary screw compressors. When used on centrifugal compressors, quite efficient results are obtained, particularly with the use of inlet guide vanes, which direct the air in the same direction as the impeller inlet (Lawrence Berkeley National Laboratory 2003). However, the amount of capacity reduction is limited by the potential for surge and minimum throttling capacity. On the other hand, modulating control is an inefficient means of varying compressor output for lubricant-injected screw compressors. In fact, throttling the inlet valve creates a relatively high energy requirement, due to the higher pressure ratio. Inlet valve modulation is normally limited to a range from 100% to about 40% of the rated capacity. At this point, it is more efficient to let the compressor operate fully unloaded, like a compressor using load/unload controls. Figure 23 illustrates typical performance curves for compressors where inlet valve throttling is used, with and without unloading the compressor. As it can be seen, when working at 40% partial load, the compressor still uses around 80% of the power required when operating at full capacity, meaning that its efficiency is halved.

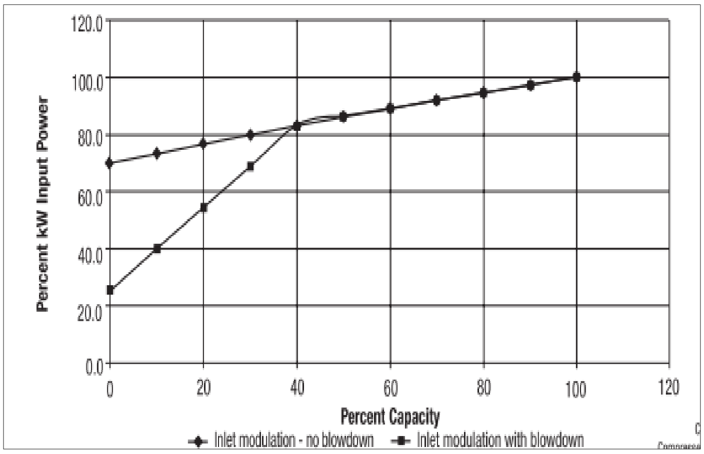

Figure 23 - Rotary screw compressor performance with inlet modulation control (Lawrence Berkeley National Laboratory, 2003)

4. Variable Displacement

This type of control is also referred to as multi-step part load control. Some compressors are designed to operate in one or more partially loaded conditions. With such a control system, the output pressure can be more closely controlled without requiring the compressor to start/stop or load/unload (Lawrence Berkeley National Laboratory 2003). Reciprocating compressors are designed as two-step (start/stop or load/unload), three-step (0, 50, 100 percent) or five-step (0, 25, 50, 75, 100 percent) control. Some lubricant-injected rotary screw compressors can vary their compression volumes using special capacity control valves, typically sliding or turn valves. With a variable displacement control scheme, the output compressed air flow and compressor power consumption can be more closely controlled without having to start/stop or load/unload the compressor. As it can be seen from Figure 24, such control scheme generally exhibits an almost direct relationship between motor power consumption and loaded capacity. Efficiency is especially good for loading conditions above 60%, but it decreases at lower loads.

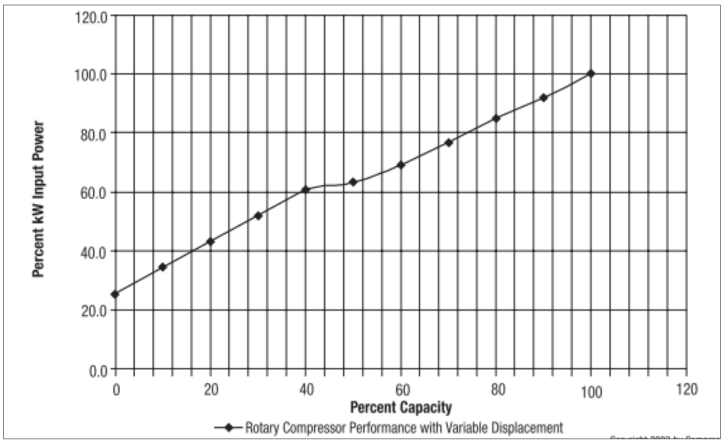

Figure 24 - Rotary screw compressor performance with variable displacement control (Lawrence Berkeley National Laboratory, 2003)

5. Variable Speed Drive

Compressors with a motor drive whose speed is controlled electronically provide an optimal opportunity to keep the compressed air constant within a small pressure range (± 0.1 bar). Basically, a Variable Speed Drive (VSD) continuously varies the speed of the compressor to meet changes in the system demand. A frequency converter, which regulates the speed on a conventional induction motor, is an example of such control method. The compressor's capacity can be adapted to the precise air requirement by continuously measuring the system pressure and letting the pressure signals to control the motor's frequency converter and, thus, the motor's speed (Atlas Copco 2015).

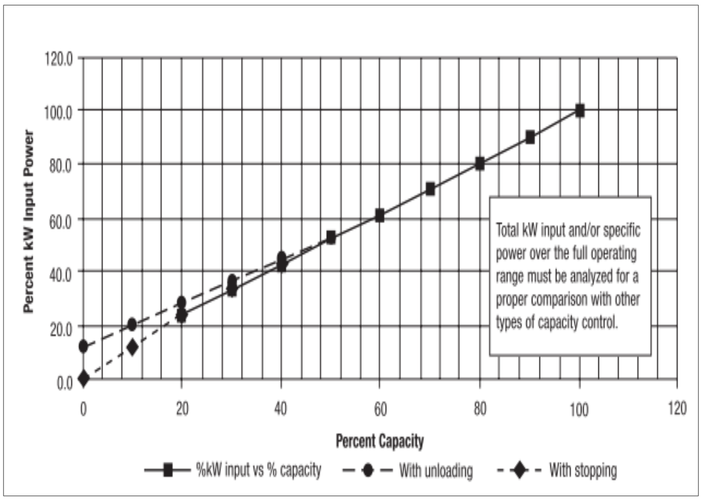

Figure 25 - Rotary screw compressor performance with VSD control (Lawrence Berkeley National Laboratory, 2003)

Both lubricated and oil free screw compressors can be equipped with variable speed drive. When air loading drops below the minimum speed of the drive, the compressor usually operates in on/off or load/unload control. In most cases a variable speed drive compressor offers the most efficient part load operation, as shown in Figure 25 by the nearly proportional reduction of compressor input power and output air flow.

MULTIPLE COMPRESSOR SYSTEM CONTROLS

The basic goal in controlling multiple compressors is to maintain the lowest and most constant pressure, through all flow conditions, while ensuring that all running compressors except one are either running at full load or off line. The remaining compressor (which is called the trim unit) should be the one most capable of running efficiently at partial loads. To achieve the stated goals, systems with more than one compressor require advanced control strategies, that coordinate compressors' operation and air delivery to the system (Lawrence Berkeley National Laboratory 2003). The main types of multi compressor control are briefly described below.

1. Cascaded Pressure Band Control

This type of control is the simplest method of coordinating multiple compressors. With this control strategy, the local compressor pressure switch controls are arranged in an overlapping or cascaded pattern. The idea is that compressors are loaded/unloaded (started/stopped) depending on system's pressure, which, in turns, depend on compressed air demand. This system control can avoid part load compressors, but can still present the problem of approaching production's minimum pressure requirement. In fact, because of the overlapping of the pressure bands of the various compressors, it often leads to higher than necessary pressures during partial loads (Lawrence Berkeley National Laboratory 2003).

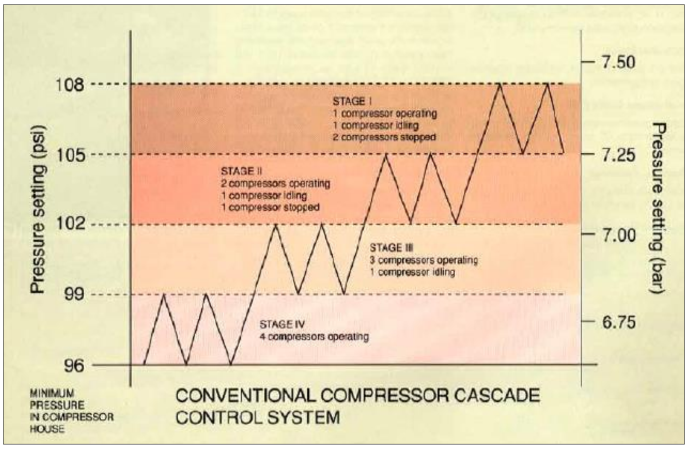

Figure 26 - Cascaded Pressure Band Control (Anglani & Mura 2010)

2. Network Control

This type of control uses the optional feature of the local compressor control to communicate with other compressors to form a chain of communication, and uses single set-point logic to make operational decisions (e.g. start/stop compressors). In systems with positive-displacement compressors, all compressors are kept fully loaded except for one that is operated in some part-load condition (Lawrence Berkeley National Laboratory 2003). Despite network controls are more sophisticated and efficient than simple cascaded pressure band controls, they still have some drawbacks, such as:

- they are able to control only air compressors;
- they cannot be networked with remote compressor rooms without a master control;
- typically, they only work with compressors of the same brand and configuration because of micro-processor compatibility issues.

3. System Master Controls

A system master control is the most sophisticated control type, which uses single-point control logic with rate-of-change dynamic analysis to make decisions regarding how the compressed air system responds to changes (Lawrence Berkeley National Laboratory 2003). These changes can occur on the demand side, supply side, or in the ambient conditions, and they all affect the performance of the system and have a role in how the system should respond. A properly configured system master control can determine the best and most energy-efficient response to any of these events. The number of elements that this control can interface is limited by practicality and cost. Some of the functions that can be performed by a system master control include:

- send/receive communications;
- select which compressor should be started/stopped relative to change in system demand;
- change base/trim duties;
- select appropriate mix of compressors to optimize efficiency;
- monitor dryer dew point;
- monitor filter differential pressure; and
- monitor condensate trap function.

2.2.4 Compressor cooling

The laws of thermodynamics dictate that heat is an unavoidable by-product of compression. More than 80 percent of the electrical energy going to the compressor is converted into thermal energy. A properly sized cooling system is crucial to remove the heat from the compressor unit and from the compressed air. Ultimately, this is performed by heat exchangers that use two types of coolant:

- water; or
- air.

Water cooling is more effective because of its greater absorption capability per unit volume. However, its supply and disposal at reasonable cost may be a problem. When the availability of water is sufficient and cost-effective, the feasibility of an open cooling system should be evaluated. This uses the water supplied by an external source such as a lake or municipal water, forces it through the compressor, and then discharges it as wastewater. When this is not possible, it can be opted for an open system with circulating water (cooling tower) or a closed system (water/air or water/water heat exchanger) (Atlas Copco 2015). In any of the three cases, the quantity of water required can be reduced if a control system is used to vary the flow in response to cooling demands of the system, measured for example with the water discharge temperature. Figure 27 shows the scheme of a closed cooling system removing the heat generated in two compressors.

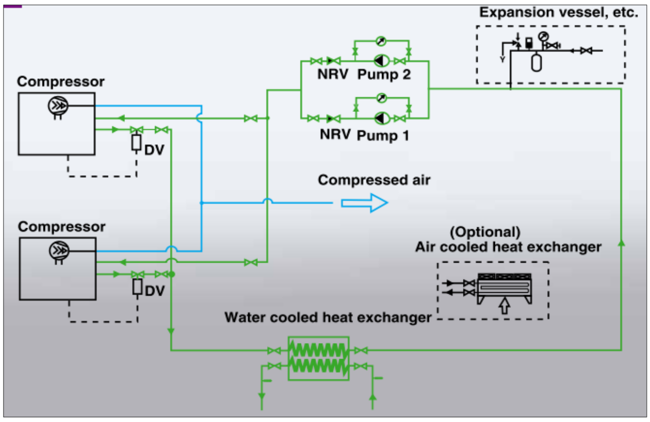

Figure 27 - Schematic of a closed cooling system (Atlas Copco 2015)

Air cooling, instead, uses a ventilation system that forces atmospheric air inside the compressor package. For the smaller units such as low duty-cycle and low power single-acting piston compressors, natural convection may be sufficient. Although air is less effective than water in removing heat, air cooling may simplify heat recovery. This is because heat recovery from air does not require the typical additional stage of heat exchange which is needed to recover heat from water. When talking about compressor cooling, there are three possible elements which need to be cooled: the compressor unit, the intercooler (if present), and the aftercooler (if present).

Compressor unit

Compressor units can be cooled with air, water, and/or lubricant. The type of compressor largely defines the type of coolant used, even though compressor size and duty cycle are also relevant factors. Single-acting piston compressors are typically cooled by air exploiting a series of fins along the outer wall of the compressor, which increase the surface area of heat exchange. Frequently, the compressor fly-wheel is designed to serve as a fan to force additional air across the cylinders. Large double-acting reciprocating compressors are normally water cooled. They have built-in cooling water jackets around the cylinders and in the cylinder heads (Figure 28). The cooling water in non-recirculated systems is typically cooler than ambient air, so the cooling water should be run through the intercooler and aftercooler first to reduce thermal stress and the chance of creating condensate inside the compressor (Talbott 1992). Centrifugal compressors are generally water-cooled. As mentioned before, oil-lubricated rotary compressors use the injected lubricant to remove most of the heat of compression. In turn, the lubricant must be cooled before it is reinjected in the air end. This can be accomplished either by air- or water-cooled heat exchangers.

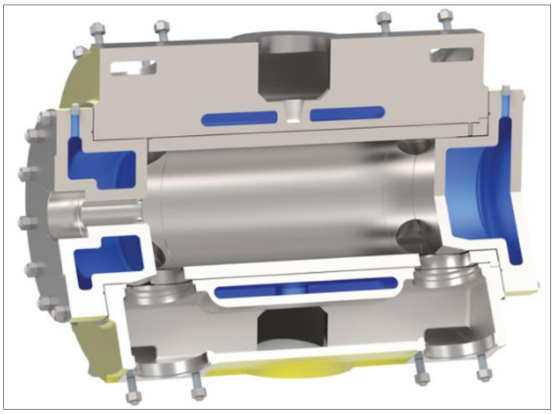

Figure 28 - Drawing of a water-cooled cylinder

Intercooler

As previously discussed in the chapter, often air is pressurised in more than one step using compressors with two or even more stages. To maximise the benefits delivered by a multi-stage compression, intercoolers can be used. An intercooler is a heat exchanger that cools the air at the outlet of a stage, before it enters the successive one. Intercoolers, as any other heat exchanger, should be cleaned periodically. A dirty heat exchanger costs in two ways: warmer air due to lower heat transfer capability, and higher pressure drop due to air flow obstruction (Talbott 1992). Furthermore, as water vapour condensation occurs, a separator and a drain should be fitted.

Aftercooler

Typically, the temperature of the air exiting the compressor is 80 – 170 °C. Some industrial systems can distribute uncooled air, simply as it leaves the final compression stage. Certain forges, foundries and processes can use this hot and wet air. However, such installations are rare, and almost all systems are equipped with aftercoolers, which lower the temperature and remove water from the air (Talbott 1992). In some systems, after-coolers are an integral part of the compressor package, while in other systems the aftercooler is a separate piece of equipment. Some systems have both.

Some of the criteria for the selection of an aftercooler are: required discharge temperature, required dryness, air inlet temperature and humidity, temperature at using point, availability and cost of cooling water, cost of blowing cooling air. The aftercooler is important also when a dryer is installed, to reduce the load on the dryer. Furthermore, dryers normally have a maximum recommended inlet temperature, and this specification must be met. Oversizing the aftercooler may be also a good investment, to both reduce the pressure drop and the discharge air temperature. Because a lot of water vapour will condense, a separator (not oversized) and a trap must be fitted. Figure 29 below shows the flow diagram of a typical manufacturing plant air installation using an oil-lubricated rotary screw compressor. With the arrangement shown, the lubricant and the compressed air flow through separate heat exchangers cooled by the same fan.

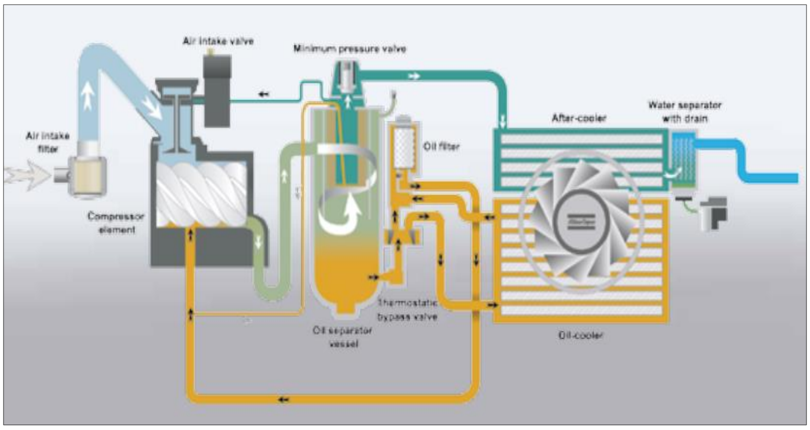

Figure 29 - Oil-lubricated rotary screw compressor flow diagram
(Atlas Copco 2015)

2.3 Conditioning equipment

2.3.1 Compressed air storage

Storage is a critical part of any properly designed air system. When correctly applied, storage can improve energy savings, air quality, pressure stability, as well as reduce maintenance costs and extend the life of the air compressor (Kaeser Compressors 2008). A primary air tank is usually located close to the main compressor(s), upstream and/or downstream of the clean-up equipment. It acts as general system storage, decoupling the demand and the supply sides. It is possible to identify three main functions of the air storage:

- it dampens the pressure fluctuations generated by reciprocating compressors;
- it stores compressed air to cover peak demand; and
- it cools the compressed air.

When reciprocating compressors are used, the primary air receiver is crucial to dampen the pressure pulsations in the air stream. This is very important, so small reciprocating units are usually directly installed upon the receiver, which is used as basic mounting frame for the assembly of the compressor and the accessories.

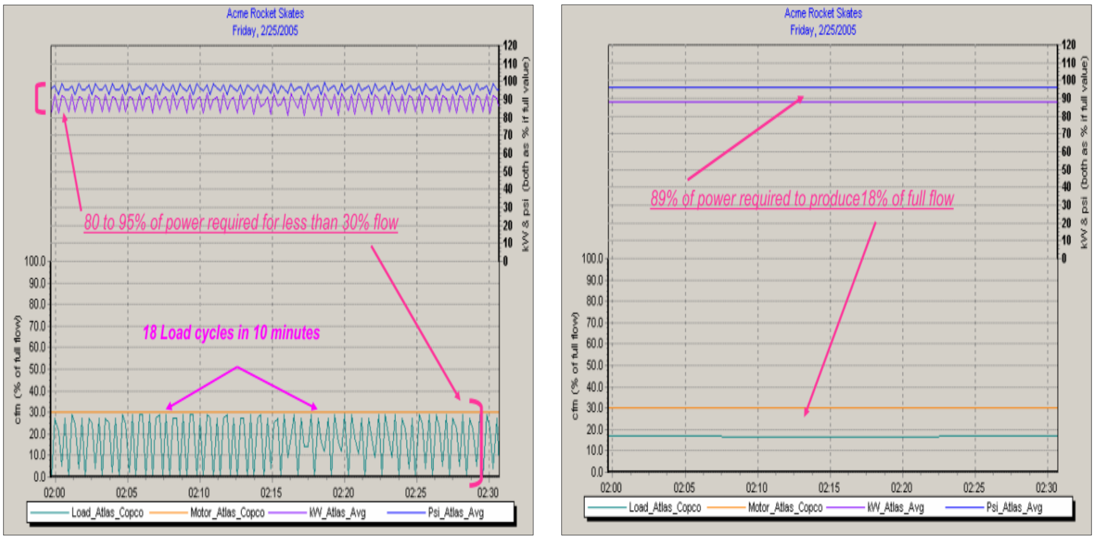

Figure 30 – System with inadequate storage: a (left) rapid cycling; b (right) high average energy consumption (Kaeser Compressors 2008)

The second and most important function of a primary air receiver is to provide a larger system capacity. This increases the cycle time of the compressor control system, and makes less difficult the elimination of unstable and overcorrecting control cycles. Figure 30 (a) shows a recording from a system with insufficient storage. The horizontal axis indicates the observation time (minutes), the left-side vertical axis reports the air flow rate as a percentage of the full capacity, and the right-side vertical axis indicates the power consumption and the discharge pressure, evaluated against the respective full load values. The graph shows the rapid-cycling of the compressor (on the bottom), which is evident in that the unit conducts 18 cycles every 10 minutes. This means that the compressor remains unloaded (zero cfm), or loaded (100% cfm), for less than 30 seconds. Figure 30 (b) shows the data averaged over 15 minutes. It can be noted that the system requires an average of 89% of full load power to produce only 18% of full load flow, which is quite an energy-inefficient performance (Kaeser Compressors 2008).

Let us now compare these results with the energy performances of a system where the minimum recommended storage level has been installed. Figure 31 (a) shows how such an adequate storage allows the compressor to reach the lower unloaded energy state. This is accomplished by the storage supplying air to the system long enough for the unit to complete the blow-down process between each cycle. This permits the compressor to reach the fully unloaded state between cycles, reducing the average energy demand required to maintain the system. Averaging the data over 15 minutes, the compressor requires 52% of full load power to produce 36% of full load flow, as illustrated in Figure 31 (b).

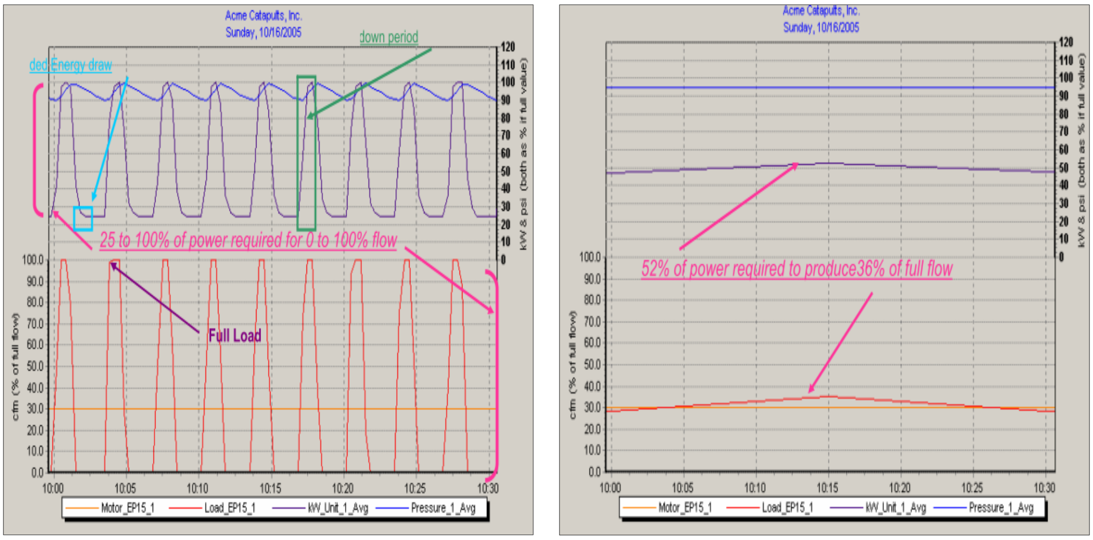

Figure 31 - System with adequate storage: a (left) low-cycling; b (right) low average energy consumption (Kaeser Compressors 2008)

About the location of the primary air receiver, there are two options:

- upstream the dryer; or
- downstream the dryer.

When storage is placed directly after the compressor(s), it is commonly referred to as "wet-storage". The main advantage of a wet storage is that it allows the settling of some free water and oil from the air stream, reducing the amount of moisture which must be removed by a subsequent drying stage. In fact, because the air entering the receiver is reduced in velocity and cooled, some of the moisture condenses and falls to the bottom of the receiver, where it can be removed by a trap. In this regard, it is desirable that the air-entry to the receiver is located below the centre, whereas the discharge near the top, to minimise the carry-over of the entrained liquids. A disadvantage of a wet-storage is that the stored energy is located before any air treatment equipment, such as filters and dryers. If demand exceeds the rating of the air treatment equipment, the dryers and filters will not be able to properly process the air to the required quality level, so that some moisture and oil will pass through to the end-use equipment. Overflowing the dryer and the filters will also create excessive pressure drops, may shorten the life of these elements, and increase their maintenance needs (Kaeser Compressors 2008).

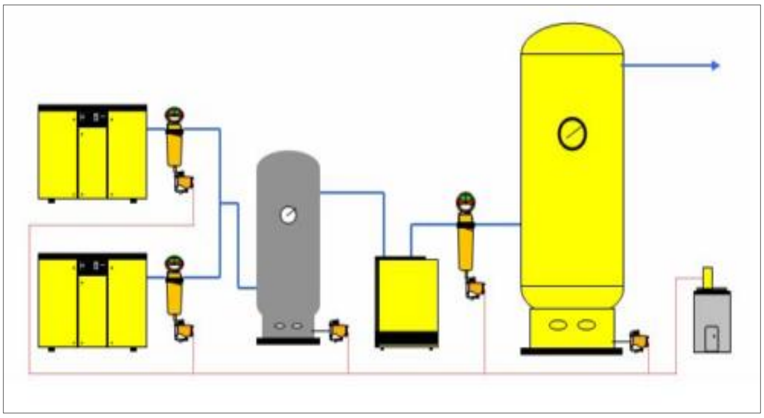

Figure 32 – Design arrangement with wet and dry air receivers
(Kaeser Compressors 2008)

Storage located after the air treatment equipment is referred to as "dry-storage". The advantage of dry-storage is that all the stored energy is processed and ready for use when needed. With dry-storage the air treatment equipment can be easily sized based on the compressor(s) capacity, and there is a significantly lower risk of overflow. However, the advantage of air cooling and condensate separation is lost. One way to solve this dilemma is to install storage both upstream and downstream of the dryer, with the dry-storage being the larger share, and the wet-storage often comprising no more than 33% of the total capacity (Kaeser Compressors 2008). This design solution is represented in Figure 32 in the previous page.

Some compressed air systems can benefit from additional secondary air receivers located somewhere in the distribution network. This is especially true when there is equipment located at the end of a long air distribution pipe, or machinery requiring large amounts of compressed air for short periods of time. This condition often results in severe localised pressure fluctuations with many essential end points starving for compressed air. If the intermittent demand occurs over a short duration, it may be possible to supply the required air directly from the secondary storage tank rather than running added compressor capacity. In general, facilities with large fluctuations in air demand, or with insufficient air pressure in decentralised areas of the system should evaluate the need for one or more secondary air tanks (Kaeser Compressors 2008).

2.3.2 Air filters

Air filters are used to remove contaminants, especially solid particles, oil, and water from the air. Different types are used for different requirements and locations within the system. For the sake of clarity, it may be convenient to distinguish between compressor inlet filters (placed upstream the compressor) and compressed air filters (positioned downstream the compressor).

Compressor air inlet filters

It is important that the particulate matter is removed before entering the compressor. Air inlet filtration reduces the compressor maintenance and possible compressor damage due to ingestion of medium-size and large particles. Also, proper filtration prevents the build-up of contaminant on the impellers of dynamic compressors, resulting in depression of surge margin and requiring preventive maintenance. Three types of inlet filters are normally used, and in increasing order of efficiency are (Talbott 1992):

- Viscous impingement filters. They depend upon a base of multiple layers of screen or fibrous material coated with liquid, frequently oil, which causes particulate matter to adhere to the filter base. The efficiency decays quickly as the oil is dried, thus it is required a periodic cleaning of the filter base from the impurities and replacement of the oil coating (indicatively every 50-100 working hours).
- Oil bath filters (Figure 33). They draw the air through an oil reservoir located in the bottom of the filter. The air and oil particles flow up through a screen mesh or other elements

which clean out the oil and the dust particles. The oil circulation ensures continuous washing and moistening of the filtering elements, resulting in lower maintenance requirements.

- Dry filters. These simply strain contaminants from the air by using densely spaced materials which block the particulate passage. This type of filter has the highest filtration efficiency, and a low pressure drop. Maintenance consists simply of replacing the element. This is typically the best filter of choice except for very high, steady flow situations.

Even if the first two types may be less costly in service if the cost of cleaning is less than that of filter replacement, they are not suitable for use with oil free compressors. Also, it is possible that two stages of filtration should be indicated for some compressor types, particularly for non-lubricated designs, because of the sensitivity of these compressors to the build-up of contaminants on impellers, screws, and cylinder walls. Multistage filters (eventually of different type) should be also used for severe filtration requirements.

In general, when selecting the filters, consideration must be given to the pressure drop which occurs across them. Among all the filters that can be found in a compressed air system, the inlet filter is especially important. Too great pressure drop across the inlet filter reduces both the compressor mass flow capacity and its part load operating efficiency. Each one percent decrease in suction pressure due to the pressure drop across the filter, costs one percent in compressor mass flow and efficiency. Thus, the compressor inlet filter should offer as small pressure drop as possible, and should be regularly maintained. Also, consideration should be given to increasing the size of this filter to assure maximum compressor capacity (Talbott 1992).

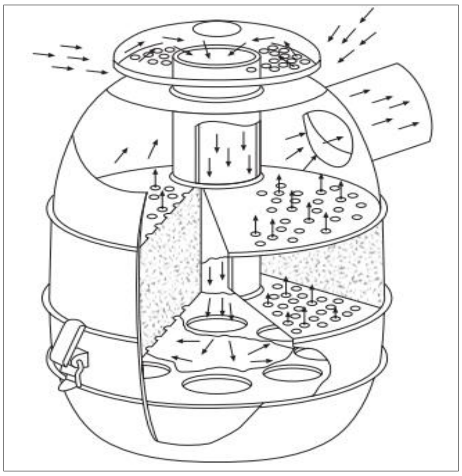

Figure 33 - Oil bath compressor inlet filter
(Belforte 2005)

Compressed air filters

Air should be filtered after the compression to remove oil, water, and any particulates produced in the compression or drying processes. The system air quality specification ultimately determines the nature of the filtration equipment. Depending on the level of air purity required, different levels of filtration and types of filters can be used. The main types of compressed air filters are (Talbott 1992):

- particulate filters, used to remove solid particles;
- coalescing filters, which coalesce particles and hydrocarbon mists into larger droplets for separation (some manufacturers combine particulate and coalescing filters into one unit);
- adsorption or activated charcoal filters for removing odours and hydrocarbons.

When dryers are included, the filtration may be critical. A desiccant type dryer normally will require a high-quality coalescing filter installed upstream to avoid contamination of the desiccant material. A particulate filter normally is installed downstream from such dryer to prevent adsorption materials from being carried into the distribution system. Some refrigeration dryers require coalescing filters upstream to keep the surfaces of the heat exchangers free of varnish. If a further reduction of oil carry-over is required downstream of the dryer, then another coalescing filter should be installed after the dryer (Talbott 1992).

It is important to say that it is not economical nor energy efficient to provide contaminant removal to an extent greater than that required by the using system. Filters should be selected carefully as they may be a relevant concentrated pressure drop component in the system. Thus, it is important not to over-specify the air filtration requirements of a system. Many plant air systems do not require oil free or highly filtered air. Furthermore, the factories that have localised requirements for such air can use localised air filtration systems. In many cases, it may preferable to apply additional filtration at the point of use if there are just few applications requiring oil free air (Talbott 1992).

A last remark is about replacement of clogged filters. Because the pressure drop across a filter increases with use, proper maintenance should be scheduled. In this regard, filter differential pressure gauges are good investments for accurate determination of filter condition. The same can be said of filter differential pressure signals, which emit an annoying sonic signal to command maintenance attention to a dirty filter (Talbott 1992).

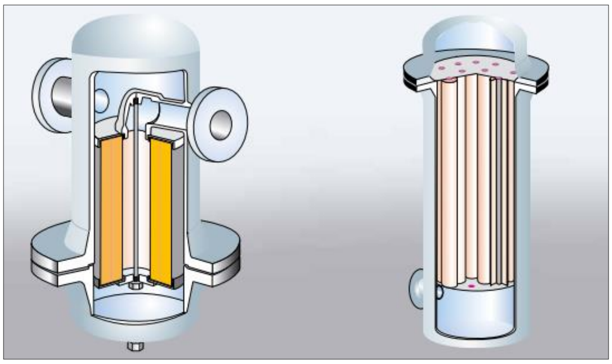

Figure 34 - A particulate filter (on the left) and a mist filter to eliminate dust, oil and water (on the right) (Atlas Copco 2015)

Separators

Separators should be installed in the system at any point where it is desirable to remove entrained liquids. Depending upon inlet air quality, this might be before the first stage of compression or immediately after the compressor intercooler. Installation of separators after air compression also reduces the amount of oil and water in the compressed air (Talbott 1992).

There are several types of separators, one being the gravity-type, which consists of a large volume that permits gas velocity to be lowered so that particles can settle out. However, this is not the most popular because such a large volume requires space and is costly. The most popular types are instead those which separate by rapidly changing the direction of the air stream so that particles are centrifugally removed from the air. These are the impingement, centrifugal, and cyclone types (Talbott 1992). As an example, Figure 35 shows a centrifugal separator. The inlet air is constrained to flow in tangential direction and at high velocity, following an helicoidal trajectory, to later exit through a central axial path. The centrifugal force that acts on the solid particles and liquid droplets during the helicoidal motion pushes them against the filter walls. In this way, the contaminants adhere to the walls, and flow to the bottom of the separator, where they are collected, before being manually or automatically removed. In general, all separators should be equipped with drains for removing the condensate (Belforte 2005).

Importantly, impingement, centrifugal, and cyclone separators are all designed for a specific flow rate, since the flow rate determines the velocity and, hence, the centrifugal force. Thus, differently from the other types of filters, separators must not be oversized. If the flow rate is expected to be highly variable, then it may be desirable to connect several separators in series, each designed for a different band of air flow rate (Talbott 1992).

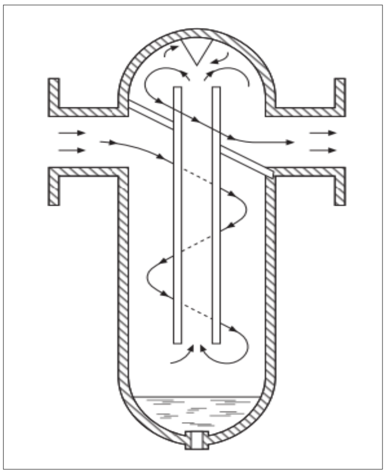

Figure 35 - Centrifugal separator (Belforte 2005)

2.3.3 Air dryers

Before entering the details of the different drying technologies, it is worth introducing some basic concepts related to the air humidity. The first thing to say is that the amount of moisture which can be absorbed as a vapour and remain mixed with the air is determined by the temperature and the volume of the mix. The implication of this is of high importance for the correct operation of the compressed air system (Talbott 1992).

Even in dry climates, the air supplied to the inlet of the compressors always contains some water vapour. The quantitative measure of this vapour is the specific humidity. Relative humidity is a measure of the amount of vapour in the air compared with the maximum amount that the air can absorb at that specific temperature and pressure. Since air at higher temperatures can hold in absorption more water, heating the air (without changing the moisture content) will lower the relative humidity, and vice versa. When air is cooled to the point that relative humidity reaches 100 percent and then is cooled further so that some moisture begins to liquefy, then the air is said to be at its dew point (Talbott 1992).

When air is compressed, the volume is reduced, so that the moisture that had been absorbed in a large volume of air is compressed to a much smaller space. Hence, the effect of compression is to raise the specific humidity. However, since most compression processes are nearly adiabatic, the temperature of the air rises as well, permitting more water to be retained in absorption by the air, as it is at higher pressure, but also much warmer (Talbott 1992). In other words, in the compressor the effect of the temperature rise is prevalent over the effect of the pressure increase, so that no condensation occurs.

The problems of condense formation come downstream in the system when the air is cooled. Some of the condensed water is removed by inter-cooling, aftercooling, separation, and filtration as the air drops in temperature (Talbott 1992). Moisture condensation and subsequent elimination does not assure dry air. In fact, the problem is that the relative humidity of the air is about 100 percent when it exits the after-cooler. Hence, without drying, the compressed air would enter the distribution system in a saturated condition, and typically at a temperature higher than many portions of the distribution system, tools, and pneumatic devices. The result of such situation would be system-wide condensation, eventually leading to:

- pipe and valve corrosion;
- higher maintenance costs of tools and pneumatic devices; and
- air loss due to more frequent line purging and blow-down.

Besides these drawbacks stemming from the formation of condensate all over the distribution system, wet air is not desirable for almost any compressed air tools, particularly for instrumentation. When compressed air is used as a process ingredient the drying needs may be even more strictly, and should be specified by the process engineers. For all these reasons, the operation of compressed air systems is improved if the air is adequately dried.

The drying extent is usually expressed with the “pressure dew point” (PDP), i.e. the temperature at which air becomes saturated at a specific working pressure. Basically, low PDP value indicates small amounts of water vapour in the compressed air. Typically, the lower the dew point required, the higher the investment and operating costs for air drying. For this reason, it is not cost-effective to over-dry the compressed air above the actual system needs. For example, if a portion of the factory needs especially dry air, it may be economic to furnish a dryer only for that portion. Also, some factories have two separate distribution systems, one supplying a large demand for dry air and the other a comparable need for less dry air (Talbott 1992).

As a rule of thumb, unless there are special needs from compressed air users, it may be sufficient to keep the PDP (at least) 5°C below the minimum temperature that can be found in the system. As an example, if the minimum foreseen temperature is -10 °C, the pressure dew point should be at least -15 °C, to avoid the condensation of the moisture and the subsequent formation of ice. Although these are not the only ways, there are three most common techniques for removing the moisture from compressed air (Belforte 2005):

- absorption;

- refrigeration; and
- adsorption.

The corresponding types of dryers are the most common in the industry, and are individually described below.

Deliquescent dryers

They are often referred to as absorption dryers. This type of dryer can lower the dew point only to a limited extend. Nevertheless, if the compressor is equipped with a good after cooler and separator, and if the distribution system does not have lines outside the factory building, then the deliquescent type dryer may be sufficient.

An absorption dryer is simply a pressure vessel containing water-absorbing chemicals, which melt away in time. The most common deliquescent materials for compressed air drying are salts of sodium, potassium, calcium, and those with a urea base. Various compounds of these have been developed and sold under a variety of trade names (Lawrence Berkeley National Laboratory 2003). The main advantage of the deliquescent dryer is that it has a low initial cost, and uses no energy (except for that associated with its pressure drop). The only significant operating costs are the materials and labour required to replace the chemicals (each 4-6 months). A filter should be installed downstream of this dryer to prevent the carry-over of salts into the system. The pressure drop across this filter may be also accounted to the energy cost of the dryer when the system is designed and a dryer must be selected.

A simplified representation of a deliquescent dryer is shown in Figure 36. The wet air (A) flows towards the bottom of the tank, where it can expand and undergo a sudden change in direction, which favours an initial condensate separation. The air later flows through the absorbing salts (S), resulting in a chemical reaction which generates a solution of water, oil, and salts. While the dry air can exit the vessel from the outlet (U), the chemicals/water mix falls to the bottom of the tank, where it is removed from the drain (B), either manually or automatically. Provision must be made for designing the system to drain the chemical/water mix and dispose it properly, as it is corrosive (Talbott 1992).

It should be said that there are some applications where the performance of deliquescent dryers is not adequate to meet the system needs. For example, instrumentation, finishing, and some processing frequently require the availability of air at lower dew point that cannot be delivered by a deliquescent dryer. Therefore, other dryers will be used instead of (or in series with) the deliquescent ones (Talbott 1992).

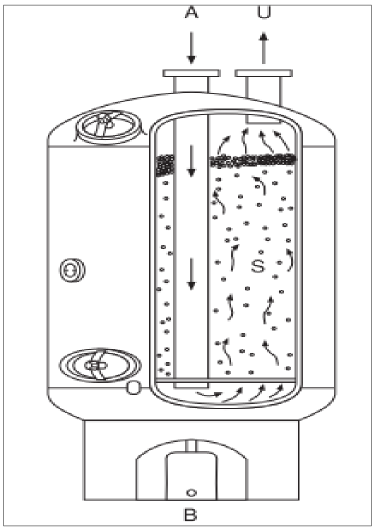

Figure 36 - Deliquescent dryer (Belforte 2005)

Refrigeration dryers

One of the most commonly used types of dryer is the refrigeration dryer. These dryers operate at moderate cost (between that of a deliquescent and a desiccant dryer) and produce air quality suitable for most indoor plant operations. Typically, they are used for dew points between +2˚C to +10˚C and have a lower limit, which is the freezing point of the condensed water.

Their working principle is based on the condensation of the moisture by cooling the compressed air using a refrigeration system. Such condensate must be subsequently separated from the air and removed from the system. Also, dry air must be heated up before entering the distribution network, to lower its relative humidity and avoid further condensation to occur.

Figure 37 in the next page shows a simplified scheme of a refrigerant dryer. The incoming compressed air (A) enters a first air/air heat exchanger (B), where its temperature is reduced using the cool and dry air exiting the dryer. In this way, two benefits are achieved:

1. it is reduced the heat load on the refrigerant circuit, and its compressor power consumption;
2. the outgoing compressed air is reheated (with no additional heat requirements), so that condensation does not form in the pipe system.

The air must be then further cooled in the air/coolant heat exchanger (C), where the cooling effect is obtained from the evaporation of the liquid refrigerant. Air and condensed moisture are then separated in (D). Finally, the dry air, after being re-heated, can exit the dryer from (E). The refrigerant system is made by a small compressor (F), a condenser (G), and an expansion valve (H).

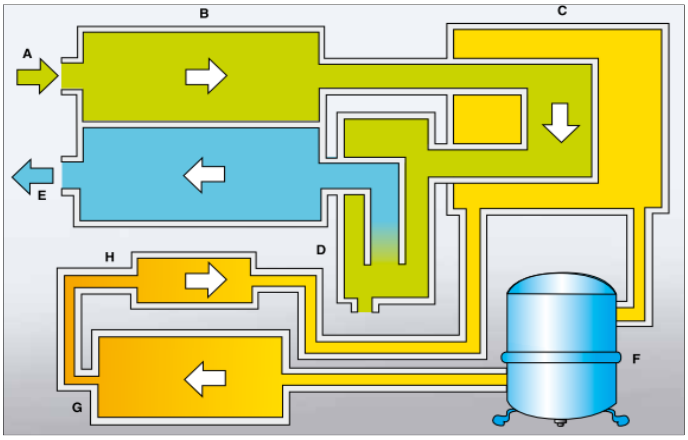

Figure 37 - Refrigerant dryer (Atlas Copco 2015)

Desiccant dryer

Desiccant-type dryers (also called adsorption dryers, or regenerative dryers) secure the driest air in absolute (Talbott 1992). They are similar to the deliquescent type, except that instead of containing a chemical which melts away, they contain a reusable desiccant (a hygroscopic material), usually silica gel, activated alumina or molecular sieve. The silica gel type can typically provide pressure dew points to - 50 °C and the maximum allowed inlet air temperature is about + 50 °C. The activated alumina type can accommodate temperatures to + 45 °C and can deliver dew points even lower (- 60 °C). Such low values of PDP make these dryers suitable for providing very dry air for the most critical applications (Belforte 2005).

It should be noticed that separation and drainage of the condensation water must always be arranged before adsorption drying. Also, if the compressed air has been produced using oil-lubricated compressors, an oil separating filter must be fitted upstream of the drying equipment. This is crucial to prevent the deterioration of the desiccant material. In most cases, a particle filter is required after adsorption drying to eliminate the desiccant fines from the air (Talbott 1992).

As said above, the desiccant material is reusable. However, the exchange of water vapour from the moist compressed air into the hygroscopic material causes the desiccant to be gradually saturated with the adsorbed water. Therefore, the desiccant needs to be regenerated regularly to regain its drying capacity. Adsorption dryers are typically built with two drying vessels for this purpose. The first vessel will dry the incoming compressed air while the second one is being purged. Each tower switches tasks when the other is completely regenerated (Atlas Copco 2015). For the industrial equipment, the typical regeneration time is between 4 and 8 hours. There are four most common methods to regenerate the desiccant. The more energy-efficient types are usually more complex and, consequently, more expensive. The different types of desiccant dryers are briefly described below (Atlas Copco 2015).

1. Purge regenerated dryer (also called "heatless regenerative dryer"). This type of dryer uses already dried compressed air to regenerate the desiccant. An uncontrolled heatless regenerative dryer constantly uses around 15–20% of its nominal capacity. A simplified scheme of this type of dryer is shown in Figure 38 (b): part of the dry, compressed air exiting the left-side vessel is deviated to the right-side tower, to regenerate its desiccant.
2. Heated purge regenerated dryer. This type of dryer takes a small amount of already dried air from the system, and passes it through an electric heater. Because heated air is more effective in stripping the moisture from the dryer desiccant, the required purge flow is around 8%. As a result, expansive compressed air can be saved (25% less energy than the heatless-type dryers).
3. Blower regenerated dryer. With this type of dryer, no compressed air is used to regenerate the desiccant material. Rather, ambient air is blown over an electric heater and brought into contact with the wet desiccant to regenerate it. The energy consumption is 40% lower than for heatless-type dryers. A simplified scheme of a blower regenerative dryer is shown in Figure 38 (a). While the left-side vessel is conditioning the incoming air, the right-side one is being regenerated by some atmospheric air blown by a fan and heated by an electric resistance.
4. Heat of compression dryer ("HOC" dryer). In a HOC dryer, the desiccant is regenerated by recovering the available heat of the compressor. Instead of evacuating the compressed air heat in an after-cooler, the hot air is used to regenerate the desiccant. This type of dryer can provide a typical PDP of -20°C without any energy being added. A lower PDP can also be obtained by adding extra heaters.

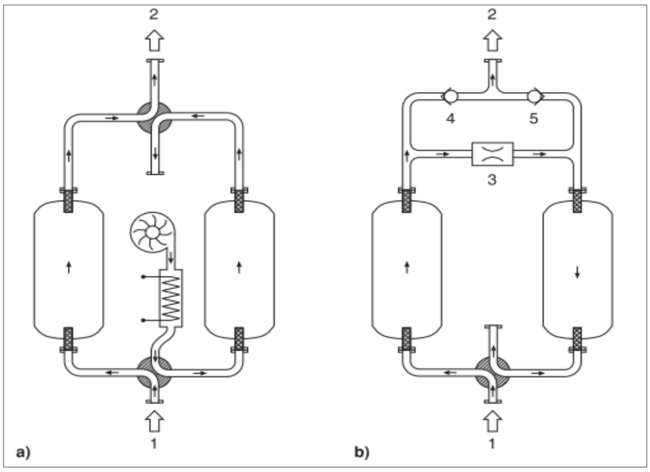

Figure 38 – (a) Blower regenerated dryer; (b) Purge regenerated dryer (Belforte 2005)

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2.4 Distribution and accessories

The distribution network is that sub-system which takes the air from the air compression, storage and treatment equipment and distributes it to the various end users. Its ultimate purpose is to serve all the compressed air applications, while minimising the system pressure losses. The distribution system mainly consists of piping connecting the components. However, also other equipment must be installed all over the distribution network to fulfil various requirements. These include traps and drains, other valves, pressure regulators and hoses (Talbott 1992).

Figure 39 shows the flow of the compressed air through the distribution system of a typical industrial compressed air installation. After leaving the air conditioning portion of the system, the air goes through a riser which takes it up to the header. Compressed air distribution systems are typically overhead, for routing convenience and availability for service and draining. The headers are the main distribution lines and supply the compressed air to the sub-headers and branch lines, which in turn feed the various drop points.

At the drop points are connected vertical drop lines, which bring the air down to the tools or work stations. These lines also should be equipped with traps or drains at their low points, to collect eventual condense. At the end of the drop line there is an appropriate fitting, which is necessary for connecting the line to the end use. In some cases, a stationary tool will be hard-connected to the piping through suitable valving. In other cases, the drop will be equipped with one or more quick disconnect fittings, so that hoses can be attached. The hoses, eventually equipped with a suitable combination of filter/lubricator/regulator, finally serve some portable pneumatic devices (Talbott 1992). In the rest of this section, the main pieces of equipment mentioned above are briefly described

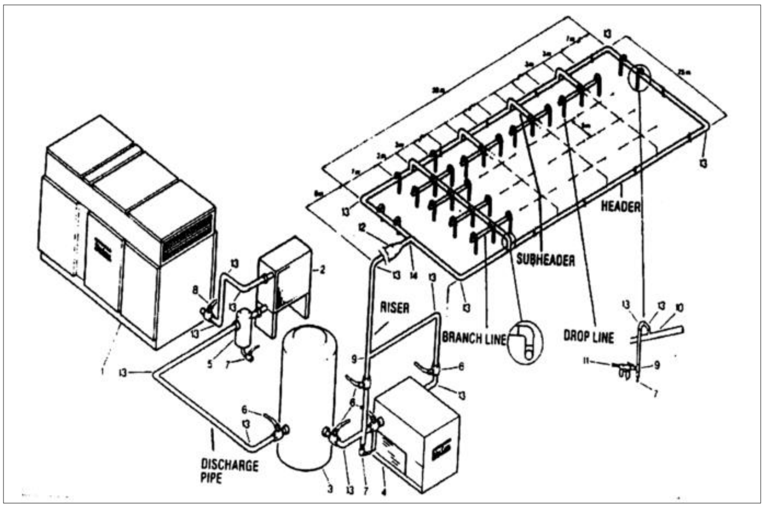


Figure 39 - Compressed air distribution system
(Aspen Systems Corporation 2001)

2.4.1 Piping

Keeping in mind the general description of a distribution system outlined above, it is useful to individually review the major pipe components, along with some basic guidelines for their correct design. Starting from the compressor room, the piping system typically includes (Talbott 1992):

- A discharge pipe. This element connects the compressor, aftercooler, aftercooler separator, receiver, filters, and dryer. It usually includes a check valve and an isolating valve. The discharge pipe from the compressor should be at least as large as the compressor discharge connection, and it is should run directly into the aftercooler.
- A riser. It connects the dryer (or the last conditioning equipment) to the main distribution header. The riser piping size and geometry are important for minimising pressure drop and maximizing contaminant removal. The riser should be one size larger than the header and/or compressor discharge line. The horizontal leg connecting the riser to the header should slope downward and it should enter the header at the side or bottom, to avoid carry-over of eventual condensate.

- The header. It is the main distribution piping for the system. The header should have a slope of 0,5 - 1 % toward a low-point drain (in opposite direction with respect to the riser), to facilitate condensate removal.
- Sub-headers. They carry the air from the header to the branch lines. The air outlet from header to the sub-headers should be taken from the top of the pipe, to minimize water carry-over. This holds also for the branch lines and drop lines.
- Branch lines. They feed groups of equipment from the sub-headers.
- Drop lines. They feed individual work stations from the branch lines. Proper removal of moisture in drop lines requires a drain in the vertical leg. Shutoff valves should not be installed in the vertical leg but in a horizontal leg. Also, the drop point should be close to the equipment using the air to minimise pressure loss in such smaller lines and hoses.

Proper design and maintenance of the compressed air distribution system is of primary importance from an energy efficiency perspective. As a rule of thumb, the distribution and conditioning systems should be sized for a combined pressure drop of no more than 10 percent of the compressor discharge pressure. Even more importantly, a well-sized and maintained network provides for proper air supply at the points of use, resulting in good tool performance and optimal production at the work station. In this regard, it is often recommendable to oversize the riser, the header, and some selected branch piping. This is a good caution against system obsolescence, permitting future growth in both plant size (new equipment) and production (higher duty cycle). Over-sized piping also provides increased buffer storage which may be even cheaper than purchasing an equivalent capacity in the form of a tank (Talbott 1992).

In regard with the layout, for many systems the best design is a continuous loop for the main header, with sub-headers running off the main header, and with branches running off the sub-headers. A loop distribution system is recommendable because it provides two-way air flow to the points at greatest distance from the compressor (Talbott 1992) In other words, a closed loop layout provides more air passages to the more distant portions of the system, resulting in a more uniform pressure at these points and reducing related pressure-drop problems. The matter of limiting pressure drops as the plant runs and maintain a constant system pressure is of great importance. This is because many pneumatic devices suffer in efficiency and effectiveness when they are subjected to pressures which are under specification (Talbott 1992). However, over-pressurisation to ensure adequate air pressure at the points of use is an inefficient practice. Instead, some changes in the system should be thought, such as the installation of additional secondary storage capacity.

2.4.2 Valves

Traps and drains

Traps and drains collect the contaminants removed from the compressed air system because of cooling, separation, filtration, or condensation, to later realise this condensate. Elimination of the condensate from the compressed air system is critical to ensure proper system performance. Also, minimising the discharge of any compressed air while the condensate is removed is of primary importance from an energy-efficient perspective. Traps should be located at any point where moisture, for any of the above or other reasons might be collected. This includes coolers, receivers, filters, separators, dryers and at any low point in a distribution line, especially if that line is passing through a cold area (Talbott 1992).

A properly installed trap will be bypassed by a manual valve, and will be preceded by a strainer with a blow-down valve, a pipe union, and a cut-off valve. These various accessories to the trap installations permit servicing the trap and removing debris from the strainer, which prevents particulate matter from fouling the trap (Talbott 1992). There are two basic methods for removing condensed contaminants:

- manually; or
- automatically.

Manual draining is the simplest method of removing condensate from the system: operators will manually open the valve to discharge the condensate. However, this technique is not practically reliable, and it is useful for small volume applications where condensate build-up is slow. When properly used, this method removes all condensate, while minimising the loss of compressed air. However, manual valves are often left “cracked open” to provide constant draining of condensate. Such practice should not be tolerated, as it can be a major source of compressed air leakage causing compressed air to continually escape into the atmosphere (Lawrence Berkeley National Laboratory 2003).

Automatic condensate traps should be used in high flow volume situations, where removal of condensate must be virtually continuous. Two main problems persist with automatic traps and drains: assurance that liquid is being fully drained from the system, and fouling of mechanical components, preventing proper drainage or positive sealing. In either case, these are serious problems as traps that are fouled closed cause condensate entrainment back into the system, whereas foiled-open traps are a major source of air leakage (Lawrence Berkeley National Laboratory 2003). Automatic traps can be further split into three categories:

- level-operated mechanical traps;
- electrically operated solenoid valves; and
- zero air-loss traps with reservoirs.

There are two main types of mechanical traps: float traps and inverted bucket traps. Both types rely on the density difference principle to open and close a discharge orifice, but their structures are quite different. A float-type trap uses a spherical element that floats on the condensate water to regulate the opening and closure of the drain orifice in a continuous way. As the condensate enters the trap, the float rises, opening the orifice and draining the condensate. When the condensate is drained and the compressed air enters the trap, the condensate level reduces, so that the floating ball closes the condensate discharge orifice. Float-type traps do not waste air when operating properly, but they often require a great deal of maintenance and are prone to blockage from sediment in the condensate. In an inverted bucket trap, instead, the air that enters the trap forces the mechanical element to float: in this condition, the discharge orifice is closed. As the condensate enters the trap, it fills up the inverted bucket, which literally sinks, thus opening the drainage orifice and discharging the water. As the condensate is eliminated, the compressed air enters the trap and let the bucket float again, so that the discharge valve is closed again. Inverted bucket traps may require less maintenance but waste compressed air if the condensate rate is inadequate to maintain the liquid level in the trap.

Electrically operated solenoid valves are equipped with a timing device that can be set to open the valve for a specified time (usually 10 seconds) at pre-set adjustable intervals (usually 15-30 minutes). There are two potential issues with using these valves. First, the period during which the valve is open may not be long enough for adequate drainage of accumulated condensate. In this case, the valve will fail to remove all the condensate leading to downstream air contamination. Second, the valve will operate even if little or no condensate is present. If this occurs, the valve will discharge significant amounts of compressed air. A possible solution is provided by using zero air-loss traps with reservoirs. These are the most energy efficient type as only condensate can be expelled, without any compressed air escapes. Because the condensate is normally gravity fed, the installation configuration is critical to prevent air lock (CEATI 2007).

A final remark is about the disposal of the removed contaminants. Oil in the form of droplets is separated partly in an after-cooler, condensation separator and it flows through the system with the condensation water. This oil/water emulsion is classed from an environmental point of view as waste oil and must not be drained off into the sewage system or directly into nature. The condensation drainage, as well as its collection, is complex and expensive. A cost-effective solution to this problem involves installing an oil/water separator, to produce clean drainage water, and to drain the oil off into a special receiver (Atlas Copco 2015).

Other valving

Besides traps and drains, distribution systems are equipped with other specialized types of valving, such as (Talbott 1992):

- safety valves to relief compressed air when the system pressure exceeds un upper threshold; there are always pressure relief valves protecting the receivers, and usually also some others located near the compressor, particularly positive displacement designs;
- shut off valves, to deviate the compressed air flow and to isolate the air supply to machines when they are not in use.

The material of the valve should be compatible with compressed air and any contaminants, especially lubricating oil, water, and trace gases. The types of valves used throughout the system can be important from an energy efficiency standpoint. For example, globe valves designed for water service are not appropriate for compressed air systems due to their high pressure drop. In general, a valve should secure three functions (Talbott 1992):

- minimum restriction and pressure drop when the valve is open;
- no significant leakage through the stem; and
- firm air shutoff in the closed position.

Valves which offer the minimum flow resistance should be selected. In fact, the pressure drop across the valve in open position is a critical factor in air system’ s efficiency. The pressure drop is a function of the valve type and port size of the valve. If the valve port size is lower than the pipe size by which the valve size is designed the pressure drop increases.

2.4.3 Pressure regulators

Pressure regulators are typically located at the end of the distribution system, right before the final hose/pipe which delivers the compressed air to the end use tool/equipment. Regulators are applied to devices that require a specific volume of air but do not require the full system pressure, which hence needs to be lowered. For example, they are frequently used to accurately control the output torque of a rotary tool or the thrust of a linear pneumatic cylinder (Talbott 1992).

It should be said that the regular and unplanned use of system-wide regulation can be wasteful. Operating the system at higher pressures than needed, with later regulation at the points of use is a waste of energy. Thus, it is recommended that the system is designed and operated so that the compressor output pressure is as low as possible, consistent with end use requirements. In many cases the pressure regulator is part of an assembly called a filter, regulator, lubricator (FRL), similar to the one displayed in Figure 40. If the tool or other pneumatic equipment is not protected from contaminants by the filter, or if it is not properly lubricated, it may wear more rapidly, reducing in efficiency, and using more air to accomplish the same job. Once again, because both the filter and the lubricator represent additional pressure drops, they should be included only when necessary.

Figure 40 - Filter regulator lubricator assembly (CEATI 2007)

2.5 End-use

Almost every industrial facility, from a small machine shop to a large pulp and paper mill, has some type of compressed air plant. In many cases, compressed air is so vital that the facility cannot operate without it. Compressed air is used in any sector, from the primary products industries supplying semi-finished raw materials to manufacturing industries. It is a cross-cutting technology, which can be employed for both process-specific and more transversal applications. In the former case, compressed air application is industry-specific, in the latter it can be used with the same purpose in different sectors (CAGI 1998).

In process service applications compressed air is used as an ingredient of the main production process rather than as an auxiliary utility. Examples in which air is used as a process service include: combustion, liquefaction and separation of gas mixtures into components, hydrogenation of oils, aeration to support biological processes, and dehydration of foods. In the beverage sector, compressed air is largely used in the production of glass and plastic bottles, where it is injected for the moulding process.

Power service includes those applications in which air is used either to produce motion or to exert a force. Typical power applications are linear actuators, pneumatic tools, clamping devices, air lifts and pneumatic conveyors. Because of their widespread use in the manufacturing industry, the various types of pneumatic tools are common applications of compressed air. The reason is that despite the higher cost of compressed air over electricity, air tools secure many inherent advantages with respect to similarly sized electric tools, such as (CAGI 1998):

- Compact size. Reduced size makes pneumatic tools easier to handle and sometimes allows them to be used in confined spaces where electric tools cannot fit.
- Lightweight. This allows to reduce operator fatigue and ultimately increases workers productivity.
- Performance. Air motors start and stop almost instantly and provide infinitely variable control of torque and speed within their capacity range.
- Longer service life. There is no heat build-up when air motors are stalled for a considerable length of time.
- Serviceability. Air tools usually have fewer parts than corresponding electric tools, and their simple construction makes them easier to repair.
- Safety. They can be operated in hazardous environments.

An important point already mentioned before is the pressure at which air is supplied to the tool. Manufacturers rate air tools to function at a specific pressure (around 6 bar(g)). If they are operated at lower pressures a decreased power negatively impacts production, reducing the tool output and efficiency. Higher pressures may result in increased performance but with the penalty of decreased tool life and increased repair costs. The quality of the work piece may also be affected by varying air pressure due to the proportional relationship between torque and supply pressure at the tool inlet. In case of painting application, the paint spray may be too sparse or too dense if the supply pressure at the gun fluctuates significantly. Close control of the air supply pressure to air tools can improve quality control and, if done properly, can reduce the energy requirement of the compressed air system (CAGI 1998).

Portable air tools can perform the more different applications. Some of the most popular pneumatic tools are drills, tapping tools, screwdrivers, riveters, nut runners, abrasive tools, hammers, saws, and routers. Figure 41 displays an operator using a portable air drill for putting holes in some furniture, whereas Figure 42 is a picture of an air tapping tool.

Figure 43 – Operator with portable air drill (CAGI 1998)

Figure 42 – Portable air tapping tool (CAGI 1998)

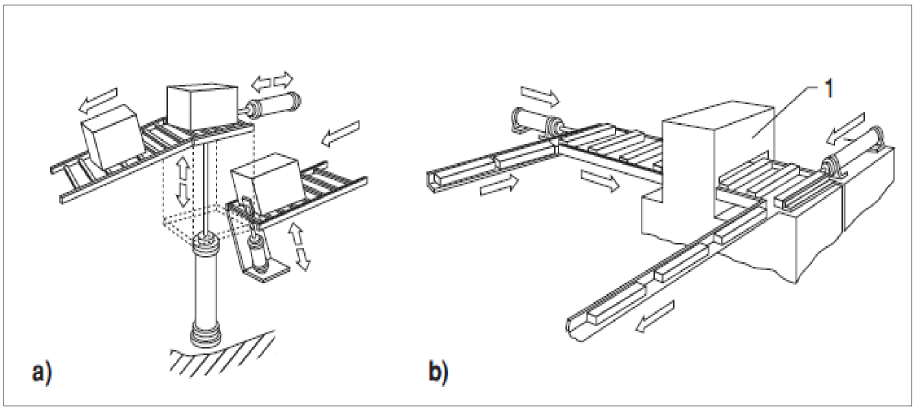


Figure 41 - Transportation systems:(a) lifting; (b) displacement (Belforte 2005)

Figure 43 shows another typical power service application of pressurised air, i.e. linear actuators in transportation systems. The lifting system in Figure 43 (a) allows to transfer boxes from a lower roller conveyor to an upper one. Three pneumatic cylinders are used to block, lift, and push the boxes. The system in Figure 43 (b) displays instead the transfer of parts along a U-shaped transportation system by means of pneumatic actuators that hit the components to deviate their movement. Some compressed air powered actuators are also installed in the enclosure (1) to move the conveyor.

Finally, Table 4 here lists some uses of compressed air in different industries. As it can be noted, power applications are not sector-specific, whereas process applications vary with the industrial sector.

Industry sector	Compressed air uses
Apparel	Conveying, clamping, tool powering, controls and actuators, automated equipment
Automotive	Tool powering, stamping, control and actuators, forming, conveying
Chemicals	Conveying, controls and actuators
Food	Dehydration, bottling, controls, and actuators, conveying, spraying coatings, cleaning, vacuum packing
Furniture	Air piston powering, tool powering, clamping, spraying, controls, and actuators
General manufacturing	Clamping, stamping, tool powering and cleaning, control, and actuators
Lumber and wood	Sawing, hoisting, clamping, pressure treatment, controls, and actuators
Metals fabrication	Assembly station powering, tool powering, controls and actuators, injection moulding, spraying
Petroleum	Process gas compressing, controls, and actuators
Primary metals	Vacuum melting, controls, and actuators, hoisting
Pulp and paper	Conveying, controls and actuators
Rubber and plastics	Tool powering, clamping, controls, and actuators, forming, mould press powering, injection moulding

Stone, clay and glass	Conveying, blending, mixing, controls and actuators, glass blowing and moulding, cooling
Textiles	Agitating liquids, clamping, conveying, automated equipment, controls and actuators, loom jet weaving, spinning, texturizing

Table 4 – Applications of compressed air by industrial sector
(Lawrence Berkeley National Laboratory 2003)

CHAPTER 3 – ENERGY EFFICIENCY INTERVENTIONS

This chapter is designed to illustrate the EEMs in the compressed air. The introductory paragraph 3.1 will set out a basic presentation of the Industrial Assessment Centres (IAC) program and database. Following, the main body of this chapter section 3.2 will provide a classification and a description of the seventeen interventions recommended by the IAC to enhance the energy efficiency in the compressed air installations. Finally, paragraph 3.3 will summarise the salient aspects of the interventions by means of a theoretical framework retrieved from the literature.

3.1 Introduction to the IAC database

The IAC program (formerly called the Energy Analysis and Diagnostic Centres (EADC) program) was created by the U.S. Department of Commerce in 1976 in response to the oil embargo and rising energy costs. It was specifically designed to support small and medium-sized manufacturing companies to eliminate unnecessary costs due to an inefficient energy use. In 1978 the IAC program moved to the U.S. Department of Energy and successively expanded the scope of the assessments to include evaluations of ineffective production procedures, excess waste production, and other production-related problems. The program relies on 28 IAC centres all over the US territory. They are teams of university-based undergraduate and graduate engineers that provide free energy, productivity, and waste assessments to small and medium-sized manufacturers. After the site visits, they develop comprehensive reports that provide specific details on all cost-saving opportunities identified during the assessments.

The IAC database (publicly available at the website https://iac.university/) is a collection of all the data stemming from the energy efficiency assessments conducted by the IAC centers. The data include information beginning in 1981 on the type of facility assessed, as well as the details of resulting recommendations. As of May 12 2017, it contains information on 17.836 assessments and 135.292 associated recommendations. The database consists of two core tables: Assessments

(ASSESS) and Recommendations (RECC). The Assessments table contains all the data specific to each assessment, whereas the Recommendations table provides all the data related to the recommendations. Here below are listed the data of the Assessments table that are of interest for the present research.

- The year of the assessment.
- The industrial sector of the assessed plant, coded with both the Standard Industrial Classification (SIC) and the North American Industry Classification System (NAICS) coding systems. The SIC index is a four-digit number with a hierarchical structure: the first two digits identify the major group to which a business belongs, the third digit allows to identify the group, and the fourth the specialisation. The codes range 2000-3999 falls within the manufacturing sector. For the database analyses presented in Chapter 4, the SIC code will be converted into the ISIC code (International Standard Industrial Classification of All Economic Activities).
- The total number of employees on site.
- The yearly revenues from sales.
- The total yearly energy consumption cost. This datum is not directly provided, but it can be easily calculated as the sum of the yearly energy consumption costs for all the energy streams used at the plant. These include electricity, natural gas, liquefied petroleum gas (LPG), fuel oil #1 (similar to kerosene), fuel oil #2 (kerosene), fuel oil #4 (a blend of distillate and residual fuel oils), fuel oil #6 (residual fuel oil), coal, wood, paper, other gas, and other energy.

The data of interest in the Recommendations table are:

- The recommendation type, coded with the ARC coding system. The ARC code is a six-digit number in the form X.YYYY.Z, where the first digit (X) identifies the recommendation type, the next four digits (YYYY) detail the strategy being employed, and the last digit (Z) indicates the application of the strategy. Energy savings recommendations are in the form 2.YYYY.Z.
- The implementation status. It indicates whether the recommendation has been implemented (within 24 months from the assessment) or not. Some recommendations figure as pending, namely the implementation status is unknown.
- The implementation cost. It is the effective cost if the intervention has been implemented, otherwise it is an estimate.

- The total yearly energy cost savings stemming from the intervention. Like the total yearly energy cost, also this datum is not directly provided. It is equal to the sum of the yearly energy cost savings for all the energy streams used at the plant.
- The simple payback time. It is calculated by the ratio between the implementation cost and the total yearly energy cost savings.

Please refer to Annex A for the full list of data included in the Assessments and Recommendations tables, the complete description of the ARC, the list of the energy resources considered for the energy consumption and savings, and the inflation rate of the dollar necessary to actualise the expenditures to the 2016 value of the money.

3.2 IAC recommendations

The Industrial Assessment Center recommends fifteen types of energy efficiency measures in the area AIR COMPRESSORS (ARC code 2,42XX). Exploiting the structure of the ARC code, the IAC recommendations are classified depending on the intervention type into two main groups:

- hardware (ARC code 2,422X), which require capital investments usually in new energy efficient machine or equipment; and
- operations (ARC code 2,423X), which consist of operations and maintenance activities that secure energy savings.

Besides the recommendations in the AIR COMPRESSORS area, other interventions are relevant for compressed air systems. Under HEAT RECOVERY FROM SPECIFIC EQUIPMENT (ARC code 2,243X), it can be found “Recover heat from air compressor” (ARC code 2,2434) and “Recover heat from compressed air dryers” (ARC code 2,2435). These interventions clearly aim at improving the energy efficiency of the compressed air systems, hence they will be included in the analyses, eventually leading to a total number of seventeen interventions. Importantly, their ARC codes are not designed to provide information on the type of intervention (hardware/operations). As it will be explained in the following of the section, these measures require the installation of physical systems for heat recovery, thus I have classified them as hardware-type interventions.

Besides the classification logics suggested by the IAC, it has been decided to use a second classification axis indicating which part of the compressed air system is affected by the intervention. Reminding the system breakdown structure used in the previous chapter, four clusters have been designed. The only expedient adopted here is the use of the term “treatment” rather than “conditioning”. The reason is that IAC recommendations target filters and dryers, but no one explicitly address the air receiver. Thus, I have decided to make this clear referring to this group of measures as treatment, rather than conditioning. The resulting interventions’ clusters corresponding to the four compressed air subsystems are:

- generation;
- treatment;
- distribution; and
- use.

In the end, crossing the two classification axes the seventeen energy efficiency measures can be grouped into eight clusters. Because there is no intervention in the treatment-operation group, the non-empty clusters are only seven. What is important to highlight at this point is that each cluster includes a set of interventions which aim at improving the energy efficiency of the same portion of system in the same way. Hence, the groups can be considered sufficiently homogeneous to make it interesting and meaningful to analyse the EEMs at cluster level.

Table 5 below reports the list of the IAC energy efficiency measures with indication of the ARC code, intervention name, targeted sub-system, and type of intervention. In the following of the paragraph, the interventions will be individually described.

ARC code	INTERVENTION NAME	SUB-SYSTEM	TYPE
2.4221	INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS	GENERATION	HARDWARE
2.4226	USE / PURCHASE OPTIMUM SIZED COMPRESSOR	GENERATION	HARDWARE
2.4224	UPGRADE CONTROLS ON COMPRESSORS	GENERATION	HARDWARE
2.2434	RECOVER HEAT FROM AIR COMPRESSOR	GENERATION	HARDWARE
2.4234	COOL COMPRESSOR AIR INTAKE WITH HEAT EXCHANGER	GENERATION	OPERATION

2.4227	USE COMPRESSOR AIR FILTERS	TREATMENT	HARDWARE
2.4222	INSTALL ADEQUATE DRYERS ON AIR LINES TO ELIMINATE BLOWDOWN	TREATMENT	HARDWARE
2.2435	RECOVER HEAT FROM COMPRESSED AIR DRYERS	TREATMENT	HARDWARE
2.4225	INSTALL COMMON HEADER ON COMPRESSORS	DISTRIBUTION	HARDWARE
2.4236	ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES	DISTRIBUTION	OPERATION
2.4235	REMOVE OR CLOSE OFF UNNEEDED COMPRESSED AIR LINES	DISTRIBUTION	OPERATION
2.4231	REDUCE THE PRESSURE OF COMPRESSED AIR TO THE MINIMUM REQUIRED	DISTRIBUTION	OPERATION
2.4223	INSTALL DIRECT ACTING UNITS IN PLACE OF COMPRESSED AIR PRESSURE SYSTEM IN SAFETY SYSTEM	USE	HARDWARE
2.4233	ELIMINATE PERMANENTLY THE USE OF COMPRESSED AIR	USE	OPERATION
2.4232	ELIMINATE OR REDUCE COMPRESSED AIR USED FOR COOLING, AGITATING LIQUIDS, MOVING PRODUCT, OR DRYING	USE	OPERATION
2.4237	SUBSTITUTE COMPRESSED AIR COOLING WITH WATER OR AIR COOLING	USE	OPERATION
2.4238	DO NOT USE COMPRESSED AIR FOR PERSONAL COOLING	USE	OPERATION

Table 5 – IAC energy efficiency recommendations for compressed air

2.4221 INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS

Gases expand as temperature rises and compression work increases with the volume of the working fluid. Thus, it takes more energy to compress a specified amount (mass) of warm air than the same amount of cool air. Usually compressors are placed inside the production plants and the intake air is normally drawn from inside the building. In many locations, the air temperature in the building is quite high because of space heaters in winter and the heat released by mechanical and electrical equipment, including the compressor and its motor. As a consequence, compressor power consumption is higher if inlet air is drawn from inside the compressor room.

A reduction of the air inlet temperature will result in lower compression work and electricity consumption. As a rule of thumb, for every 3°C the inlet air temperature is reduced, the compressor efficiency will be improved by 1 percent (Worrell et al. 2010). Air inlet temperature can be reduced placing the compressor air intake where temperature is lower. As outside air is generally cooler (and thus denser) than the air in the compressor room, it may be appropriate to route air from the outside of the building into the compressor through a separate pipe. One end of the duct is attached to the air cleaner intake or other appropriate intake port, and the other end is routed through the wall or ceiling to a cool area on the outside.

The implementation cost depends on the plant configuration and compressor location, but it is generally moderate, basically consisting of the piping material and the civil and mechanical work necessary to install the piping system. As additional ductwork will cause higher head loss on the compressor cooling fans, it may be possible that the existing ones cannot provide adequate air flow upon the installation. In this case, modifications to the cooling system are also necessary. Energy savings are generally modest as well, but they may become considerable in northern regions where temperatures are low. The fractional reduction of the compressor work WR resulting from lowering the inlet air temperature can be estimated from the following relationship (Kaya et al., 2002):

$$\mathrm{WR} = (\mathrm{W1} - \mathrm{W0}) / \mathrm{W1} = (\mathrm{T1} - \mathrm{T0}) / \mathrm{T1}$$

Where W1 is the work of the compressor with inside air [KW], W0 the work of the compressor with outside air [KW], T1 the average temperature of inside air [K], and T0 the annual average outside air temperature [K]. As an example, considering a typical compressor room temperature of 35 °C and an outside average temperature of 21 °C, ducting air from outside the building would lead to a compression work reduction equal to 4,5 percent.

2.4226 USE / PURCHASE OPTIMUM SIZED COMPRESSOR

Two conflicting factors influence the selection of the total compressor capacity needed to satisfy the system’s demand (Talbott 1992):

1. All constant speed compressors are most energy efficient when operated at full load, i.e. maximum capacity. Different designs have different part load efficiencies, but their efficiencies are maximised at full load. Thus, maximum efficiency is accomplished when the compressor is sized to handle the average load and operate at full load most of the time.
2. On the other hand, inability to meet peak loads could result in lost production and hence a much higher total cost. Undersized compressor capacity also causes reduced system pressures, potentially leading to severe reduction in output and efficiency of the equipment using compressed air, such as pneumatic tools.

The use of multiple compressors with sequential control system can be a solution to this dilemma, by providing a better match of air demand and on-line compressor capacity. Multiple compressors also secure compressor backup for maintenance and repairs, and enhance the reliability of the system. The disadvantages of a multi compressor installation are that full load efficiency of smaller compressors is generally lower than the efficiency of larger units and that smaller units are more expansive per unit of capacity (Talbott 1992).

2.4224 UPGRADE CONTROLS ON COMPRESSORS

Control mechanisms are used to match the compressed air volume and pressure delivered by the compressor with the facility demand. As air systems seldom work at full load all the time, the ability to efficiently control flow at part loads is vital. Despite proper control strategies can lead to considerable energy savings, compressors controls are frequently poorly configured.

“Upgrade controls on compressors” is inevitably quite a generic intervention’s name, because there is no such thing as a single control which is best in every situation. In fact, the type of control specified for a given system is determined by the type of compressor being used and the facility's demand profile. For example, if a system has a single compressor with a very steady demand, a simple control system may be appropriate (e.g. load/unload plus air receiver). On the other hand, a complex system with multiple compressors, oscillating demand, and many types of end uses will require a more sophisticated control strategy (Lawrence Berkeley National Laboratory 2003).

Variable speed drive (VSD) is generally accepted as an efficient means of rotary compressor capacity control. The reason is that the flow rate of a VSD compressor can be continuously regulated without efficiency losses, as a reduction of output air flow corresponds to an almost equal reduction of input power requirements. It is worth reminding that an adequately sized air receiver is still vital to reduce the cycle time of a VSD control. It is in fact there is a common misconception that VSD compressors do not require storage capacity, or anyways less storage than a Load/Unload control compressor (Kaeser Compressors 2008). Furthermore, it should be reminded that at full load a VSD compressor uses slightly more energy compared to a similar sized constant speed unit. The figure below shows how fixed-speed air ends are typically designed to operate over a narrow speed range, with significant efficiency drop as soon as they are operated off the design condition. Variable Speed Dive compressors instead are more flexible, at the expense of a lower peak efficiency in the optimum working condition.

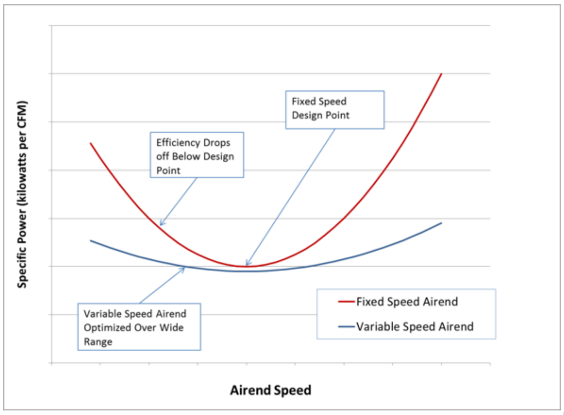


Figure 44 – Performance of a VSD vs constant-speed compressor

When multiple compressors are used, further energy savings can be achieved upon installation of a multi-unit control to reduce the part load trimming. In fact, the combined capacity of the compressors is often sized to meet the maximum demand of the facility. However, most of the time the demand is lower than the maximum. Hence, a method of control is required to coordinate compressors' operation. The basic idea behind a multiple control system is to let one or more fixed speed compressors (e.g. centrifugal type) supply the base load, and a VSD compressor to supply the fluctuating or trim load. It is important to use VSD compressors for trim/swing duty because, as stated before, they are typically the most efficient units in partial load conditions. Sophisticated multiple compressor control (such as System Master Controls) should be preferred over less performing Cascaded Pressure Band Controls.

2.2434 RECOVER HEAT FROM AIR COMPRESSOR

The laws of thermodynamics dictate that heat is an unavoidable by-product of compression. As much as 80 to 93 percent of the electrical energy used by an industrial air compressor is converted into heat (Lawrence Berkeley National Laboratory 2003). Given the large amount of compression heat, a properly sized cooling system is crucial for the correct functioning of the compressor group. Many compressed air installations offer significant and frequently unutilized energy saving possibilities in the form of waste heat recovery. Most medium to large compressors from the major manufacturers can be fitted with standard equipment for heat recovery. Because heat is energy, and because it is already there to be used, simply getting rid of it means wasting energy.

Figure 44 in the next page shows heat recovery from an air-cooled compressor exploited for direct space heating. The hot compressed air at the outlet of the compressor (C) is cooled in the air-air heat exchanger (S). The heated air is hence moved by a fan (V) through a distribution network that supplies the building to be heated. To reduce the fan power consumption and thermal losses the distance between the building and the compressor should be as low as possible. When heating is not required (such as in summer) the hot air is evacuated into the atmosphere, either automatically by thermostat control or manually by controlling an air damper. Another potential use of the waste heat with air cooling is the regeneration of the desiccant in adsorption dryers. With such application, the air from the compressors is delivered to the dryer without aftercooling.

Heat recovery for space heating is not as common with water-cooled compressors as an extra stage of heat exchange is required; nevertheless, because many water-cooled compressors are quite large (especially heavy double-acting piston compressors), heat recovery for space heating can still be an attractive opportunity. On the other hand, a potential application for recovering the waste heat of a water-cooled compressor is to supplement a hot water heating system (for temperatures up to 90 °C). Even when a normal base load of hot water from boiler is required (e.g. for washing, cleaning or showering uses), the energy recovered from the compressed air system is a supplementary heat source that reduces the load on the boiler, saving fuel and potentially resulting in the use of a smaller boiler (Atlas Copco 2015).

In general, the more energy that can be recovered and utilized in other processes, the higher the system's overall efficiency. In many cases, a properly designed heat recovery unit can recover up to 90% of the available thermal energy. Of course, the exact value depends on many factors such as number and type of heat exchanges. Part of the heat will be inevitably dissipated in the surroundings by radiation, while part of it will remain in the compressed air (Belforte 2005).

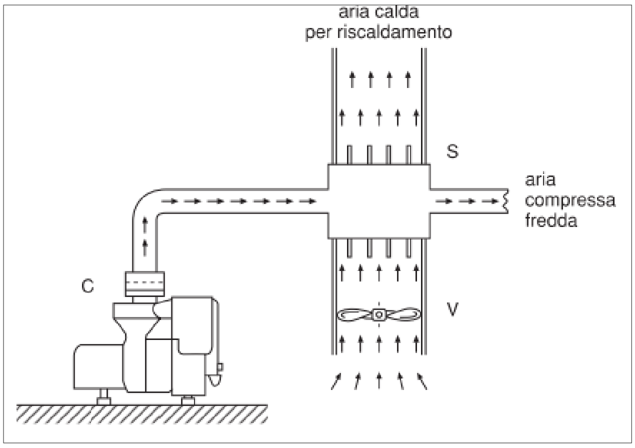


Figure 45 - Compressor heat recovery system (Belforte 2005)

2.4234 COOL COMPRESSOR AIR INTAKE WITH HEAT EXCHANGER

This intervention addresses the same inefficiency targeted by the recommendation 2.4221 INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS. The efficiency loss is the consequence of the higher work required by the compressor when the inlet air is at high temperature.

When it is difficult to draw air from the outside it is possible to cool the compressor air intake with a heat exchanger. This may be regarded as an interesting opportunity if the compressor's location and plant layout make it technically complex or expansive to realise an intake duck from the outside of the building. Also, in those regions where ambient temperature is warm or hot most of the year the use of a heat exchanger can be a valid solution. However, this intervention may require higher implementation costs than simply drawing cool air from the outside, while it provides similar energy savings. It should be also considered that the energy cost saved will be in part offset by the operative costs for running the heat exchanger, causing a longer payback time of the initial investment. Thus, this energy efficiency measure should be considered as an alternative to using outside air when the latter is unfeasible, but its cost-effectiveness should be carefully assessed.

2.4227 USE COMPRESSOR AIR FILTERS

Atmospheric air is always contaminated with solid particles, such as dust, sand, soot, and salt crystals. The degree of contamination depends on the location, and it is typically high in industrial environments, especially in some of them such as sand-blasting or wood workshops. A compressed air plant typically includes different types of filters located downstream of the compressor to remove particulates, condensate, and lubricant. However, they cannot prevent contaminants from entering the air compressor. Solid particles are especially detrimental for the compressor, because they can cause wear of the moving elements and over-heating of the unit. Operated in bad conditions, the performances of the compressor will decay over time, including energy efficiency.

An air inlet filter must always be used to protect the compressor from atmospheric airborne particles. In very dirty environments it is recommended to use also a pre-filter to increase the filtering efficacy and delay the clogging of the downstream filter. The intake air filter is the most important filter for the compressor, that should never be operated without the filter connected. Optimally sizing or even oversizing the air inlet filter is a good choice to reduce the pressure drop. Excessive pressure drop across the inlet filter has two drawbacks (Talbott 1992):

- reduction of the compressor mass flow capacity; and
- reduction of the compressor part load operating efficiency.

Once installed, the compressor intake filter must be periodically checked, as dust will accumulate over time. Normally, controlling and replacing or cleaning the air intake filter is included in the standard service routine. The US Department of Energy suggests inspecting its good status weekly or every 40 hours, and even more frequently under humid or dusty conditions (Lawrence Berkeley National Laboratory 2003).

2.4222 INSTALL ADEQUATE DRYERS ON AIR LINES TO ELIMINATE BLOWDOWN

Compressed air exiting the aftercooler is saturated with water vapor due to its thermodynamic conditions of high pressure and low temperature. As the temperature of the air reduces while it flows through the piping, equipment and tools, moisture would condensate causing damages to the piping material, such as corrosion. Furthermore, it would cause problems to the equipment which is often sensitive to liquid water. Also, if a lot of water is condensed along the lines, there is higher need to use discharge valves, which are potential sources of air escape if left open more than necessary. Drying the air is also required to satisfy system quality requirements.

Hence, the intervention simply consists of using adequate dyers that remove moisture from the air and reduce its relative humidity before it enters the piping network. However, because all dryers generate pressure drops and most of them also consume energy, it is important not to over dry. The drying level should be optimized so that the achieved pressure dew point (PDP) is sufficient to avoid condensation and match quality requirements of the end-use applications. In this regard, the performance provided by regenerative dryers are in most cases unnecessary. These dryers also require filters at the inlet and discharge which contribute several percentage points of energy loss to the system. The least energy consuming deliquescent dryers, or more likely the average energy consuming refrigeration dryers are often adequate (Talbott 1992).

Another energy saving expedient is to install a primary dryer to secure adequate drying for most end uses, and if a few applications need higher quality air just add localised conditioning equipment. Furthermore, if drying is necessary to avoid condensation rather than to meet quality requirements, then the level of air drying can be dynamically regulated to optimize the PDP depending on outside conditions (Radgen & Blaustein 2001). For example, when external temperature is higher, the required PDP can be increased, so that less drying is needed and less energy is consumed.

2.2435 RECOVER HEAT FROM COMPRESSED AIR DRYERS

There are three main types of dryers in the industrial facilities (Belforte 2005): absorption (deliquescent), refrigerant, and adsorption (desiccant). As absorption dryers exploit water-absorbing chemicals to bound the water vapour, no heat can be recovered simply because no heat is generated.

A refrigerant dryer includes a heat exchanger where the refrigerant fluid is used to cool the incoming wet and hot air. The intervention suggests recovering the heat of the refrigerant and exploit it for some useful purposes, instead of just getting rid of it. Although conceptually possible, it must be said that since the air entering the dryer has been already cooled in the after cooler, the temperature at which the heat is available in the dryer is low. Low temperature heat is a low-quality form of energy, and it is difficult to exploit.

Adsorption dryers condition the air using a desiccant material, which must be periodically regenerated. There are four main regeneration methods, and some of them may be adequate for heat recovery:

- heatless regenerated dryers use expanded compressed air purged from the system: there is no heat to recover;
- heated purge regenerated dryers use purged compressed air heated by means of an electric heater: heat can be recovered from the cooling air;
- blower regenerated dryers use ambient air heated and then blown over the desiccant: heat can be recovered from the cooling air;

- heat of compression dryers use the heat developed in the compression process to regenerate the dryer: there is no further heat to recover.

Even though heat recovery is theoretically possible with some types of desiccant dryers, the same issues outlined for the refrigerant dryers apply also for the desiccant ones.

2.4225 INSTALL COMMON HEADER ON COMPRESSORS

In case of multi-compressor installation, two basic arrangements can be identified. In the first possible configuration the compressors work independently, each having its own distribution system serving its own end-use devices. In the other one a common header connects the compressors, which supply all end-use points through the same distribution network. In this case the compressors work in parallel, with all the advantages that this entails.

First, a single header can cause lower frictional losses than those occurring in two or more separate distribution systems, especially if the new header and all the rest of the distribution system are adequately sized with a larger piping diameter capable of handling the higher air flow rate. Also, the compressors should not be too far, to limit the frictional losses in the extra piping required to connect the units.

However, the major energy savings of a common header are potential in nature, as they lie in the possibility of retrofitting a sophisticated multi-compressor control, such as a System Master Control. This would dramatically increase the energy benefits of a common header allowing to efficiently follow the system demand. This is confirmed by the fact that, among the other energy saving tips, the US Department of Energy suggests to “use parallel compressors and install multi-unit controls to reduce compressor part loading” (United States Department of Energy 2002).

2.4236 ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES

Air leaks are the greatest single source of energy loss in manufacturing facilities associated with compressed air, often wasting as much as 25 percent of the total compressed air generated by the compressor (Terrell 1998). Although leakage can come from any part of the system, the most common problem areas are: couplings, hoses, tubes, fittings, pressure regulators, open condensate traps, shut-off valves, pipe joints, disconnects, and thread sealants.

Figure 46 (a) shows the effect of the hole diameter on the power lost due to leakage in a system operating at 6 bar. The values involved are not negligible at all, considering for example that a hole with a diameter of 4 mm requires about 5 kW of extra power from the compressor. The cost associated to compressed air leaks is the cost of the energy required to compress the volume of lost air from atmospheric pressure to the compressor operating pressure. Figure 46 (b) shows such additional expenditure assuming an electricity rate of 0,05 $/kWh, constant operation, and an efficient compressor. The air lost from a single orifice with a diameter of 1,6 mm will cost about 520 $/year, a hole of 3,2 mm will cost about 2.100 $/year, and one of 6,4 mm about 8.400 $/year.

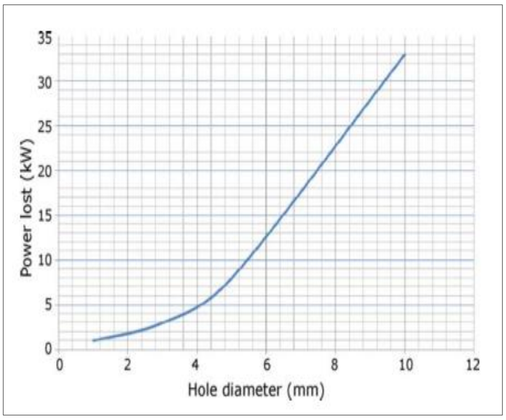
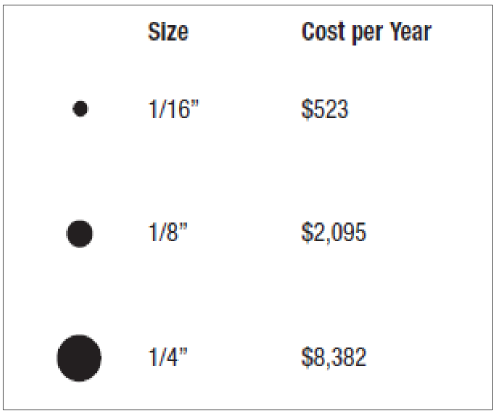


Figure 46 (a) - Power wasted in leakage for different hole sizes (Saidur et al., 2010)



	Size	Cost per Year
●	1/16"	$523
●	1/8"	$2,095
●	1/4"	$8,382

Figure 46 (b) - Dollar wasted in leakage for different hole sizes (Lawrence Berkeley National Laboratory 2003)

Fixing compressed air leaks is widely agreed to be the intervention with the largest energy saving potential. It is sufficient to say that just eliminating air leaks secures about 40% of the total energy savings that can be achieved in an average compressed air system (Radgen & Blaustein 2001). However, eliminating air escape totally is impractical, and a leakage rate of 10% is considered acceptable. Air leaks are almost impossible to see, and in environments with high background noise they are also very difficult to hear. A simple but time-consuming method to detect them is to apply soapy water with a paint brush to suspect areas. However, a better approach is to use an ultrasonic acoustic detector which can recognise the high-frequency hissing sounds associated with air leaks. Ultrasonic detectors are portable units consisting directional microphones, amplifiers, and audio filters, and normally have either visual indicators or ear phones to detect leaks. The advantages of this method include versatility, speed, ease of use, the ability to perform tests while equipment is running, and minimum training requirements (Lawrence Berkeley National Laboratory 2003).

In order to stop leaks it may be sufficient to tighten a connection, or it may be necessary to replace faulty equipment, such as couplings or pipes. Temporary repairs can also be made by placing a clamp over the hole. However, eliminating leaks is not a one-time intervention, as they will reappear after a certain time. The only solution is the implementation of an ongoing maintenance program to ensure that leak rates are continuously controlled. It should be emphasised that it is always better to avoid leaks from happening in the first place. This can be done installing fittings properly with appropriate sealants where applicable, isolating non-operating equipment with a valve in the distribution system, and selecting high quality fittings including air hoses, tubing and disconnects.

Reduction of compressed air leaks is the most cost-effective intervention to save energy in a compressed air plant, as implementation costs are generally modest whereas the resulting energy and cost savings can be tremendously high. In addition to cost savings, leak fixing secures several other non-energy benefits, such us improved production and reduced maintenance. Eliminating leaks also allows to save capital expenditures that would be required to expand compressor capacity to cope with the additional artificial demand. Overall, a good leak repair program is important to maintain the efficiency, reliability, stability, and cost effectiveness of any compressed air system (Lawrence Berkeley National Laboratory 2003).

2.4235 REMOVE OR CLOSE OFF UNNEEDED COMPRESSED AIR LINES

If an application of compressed air is eliminated or if it is not used (e.g. during night shifts) then the air flowing through the piping that connects the equipment to the header is needlessly a source of pressure drops and air leaks. As seen, this causes higher discharge pressure and higher flow rate required at the compressor, which results in greater electricity use.

This energy efficiency measure simply consists of closing compressed air lines which are no more used. When possible, air flow should be stopped as far from the operating equipment as possible. Of course, properly located shut-off valves are needed to implement this intervention (Radgen & Blaustein 2001).

2.4231 REDUCE THE PRESSURE OF COMPRESSED AIR TO THE MINIMUM REQUIRED

The system pressure directly affects the compressor’s power absorption: the higher the pressure the higher the energy needed to compress the air. In addition, raising the compressor discharge pressure wastes more compressed air due to the artificial demand of the unregulated usages, such as leaks. Operating at too high a pressure also increases the wear of tools and equipment. Briefly, excessive system pressure causes excessive energy consumption and poor system performance. Basically, there are three possible reasons why pressure may be set higher than the minimum required:

1. for no valid reason; or
2. to satisfy a critical application; and/or
3. to overcome excessive pressure drops over the system.

An example of a system operated at higher than minimum pressure without any good reason is an installation where the most demanding application requires air at 6 bar but the whole system is operated at 6,5 bar. In this case, it can be simply reduced the discharge pressure set point in the compressor room. Interestingly, as easy and cost effective as this may appear, there are a lot of air system installations which operate at higher pressures than necessary (Neale & Kamp 2009).

When a critical application requires pressure significantly higher than all the other air consuming equipment the standard solution is to operate the system at the highest pressure and fit all the low-pressure equipment with regulators. However, pressure reduction at the point of use through regulators should not be abused, as it wastes energy. A more efficient solution which deserves to be assessed is to run the system at the lower pressure and install a dedicated booster and a storage close to the critical application (Kaya et al. 2002). In case of very different pressure requirements among groups of users it may be cost-effective to use separate distribution systems operated at different pressures (Talbott 1992).

The third common reason the compressor discharge pressure is set excessively high is to overcome various pressure losses. In general, it is possible to distinguish between two types of losses: distributed and concentrated. Distributed losses are generated by the friction between the air flow and the piping. These losses depend on multiple factors, such as topology (e.g. ring or star pipe profile), geometry (pipe diameter, radius of curvature), material used, and length of the distribution system. On the other hand, any type of obstruction, restriction, or roughness in the system will cause resistance to air flow and hence punctual pressure drops. Valves, connectors, elbows, and fittings variously positioned over the system can be the cause of high punctual losses of pressure. It must be noted that air treatment equipment such as aftercoolers, filters, water separators are important sources of pressure losses as well, so they should be carefully selected and maintained. In general, a properly designed compressed air system should have a pressure loss of less than 10 percent of the compressor's discharge pressure, measured from the point of discharge to the point of end use (Atlas Copco 2015). In the broadest compressed air installations, most of pressure losses are dispersed all over the distribution network. There are several interventions to reduce frictional pressure losses in the distribution network, such as:

- use adequately large piping diameter;

- replace corroded or damaged piping;
- use looped system configurations where possible;
- eliminate unnecessary elbows, valves, and other flow restrictions; and
- minimise the length of hoses and tiny piping.

The only drawback with lowering the average system pressure is that large changes in demand can cause pressure at points-of-use to fall below a minimum threshold, leading to an improper functioning of the equipment.

2.4223 INSTALL DIRECT ACTING UNITS IN PLACE OF COMPRESSED AIR PRESSURE SYSTEM IN SAFETY SYSTEM

Valves are extensively used in any industrial plant processing some type of working fluid, such as urea, oil, water or compressed air itself. Displacement of a valve is performed thanks to an actuator connected the stem of the valve activated either automatically or commanded by an operator. This intervention suggests the substitution of pneumatic actuators with more efficient direct acting units, such as pistons powered by a crankshaft connected to an electric or internal combustion motor.

2.4233 ELIMINATE PERMANENTLY THE USE OF COMPRESSED AIR

Compressed air is extensively adopted in any industrial sector for the most different applications because it is clean, safe, readily available, and simple to use. Unfortunately, the energy efficiency of compressed air plants is extremely low, typically between 10 and 15 percent. For this reason, the US Department of Energy suggests to use compressed air only if *“safety enhancements, significant productivity gains, or labour reductions will result from its usage”* (Lawrence Berkeley National Laboratory 2003). In the other cases, other more efficient energy sources should be used such as electricity and hydraulic energy.

2.4232 ELIMINATE OR REDUCE COMPRESSED AIR USED FOR COOLING, AGITATING LIQUIDS, MOVING PRODUCT, OR DRYING

This intervention aims at eliminating or at least reducing the use of compressed air for a set of very common applications. In the process industries, compressed air has an important role in agitating, elevating, and transferring liquids, especially acids and acid solutions. Agitating function may be accomplished by means of an air pipe which enters the tank from the bottom: air issues from the opening and bubbles through the liquid provide the desired turbulence effect. Compressed air is extensively adopted to power pneumatic conveyors in the materials-handling field. Materials could be moved by air under pressure or partial vacuum: in the pressure system, the compressor precedes the system, while in the vacuum system, it follows the system. Compressed air is largely used also for drying purposes in virtually any sectors, such as in the pulp and paper where it is used to dry containers (CAGI 1998).

2.4237 SUBSTITUTE COMPRESSED AIR COOLING WITH WATER OR AIR COOLING

Using expansive compressed air for mere cooling purposes is quite an energy waste. Atmospheric air blown by a fan should be similarly effective and much less energy consuming. When economically available water is an excellent choice for cooling purposes, as its high specific heat makes it effective in removing heat. Furthermore, water pressurisation requires much less energy than air compression as water is denser than air.

2.4238 DO NOT USE COMPRESSED AIR FOR PERSONAL COOLING

Blowing compressed air for self-cooling is a bad habit of some workers that should not be tolerated. Instead, if the temperature of the working environment is too high, then the management should consider investing in an adequate ventilation or air conditioning system. This will result in compressed air savings and better comfort conditions for all the personnel.

3.3 Interventions’ summary

As a conclusion of the chapter, Table 6 provides a synthetic overview of the salient characteristics of the energy efficiency interventions described in the previous paragraph. The table is an adjustment consistent with the scope of work of the characterization framework developed by (Trianni et al. 2014). The authors identify 17 attributes that allow to fully describe any energy efficiency measure, and group them into six categories such as economic, energy, environmental, production-related, implementation-related and the possible interaction with other systems. They also test the general validity of the framework applying it to several energy efficiency measures in the cross-cutting technologies, including compressed air.

With respect to the original framework I have taken 11 of the 17 factors and their associated attributes values. Although this is a simplification of the original work, it allows to better focus on those elements that I consider more significant for compressed air interventions. Also, it has been considered an additional factor describing which part of the compressed air system the intervention acts on. The power of the model is that it represents a frame of reference providing to industrial decision-makers all the logically-structured elements that need to be considered when evaluating an investment in energy efficiency.

Within the limited purpose of this thesis, the framework offers a convenient snapshot of the EEMs in the compressed air area. As an example, let us consider intervention 2.4222 (Install adequate dryers on compressed air lines to eliminate blowdown). This is a one-time intervention consisting in the retrofit of a new piece of treatment equipment in the compressor room, which is typically located quite distant from the core process. It does not sacrifice in any manner the compressed air output to save energy, thus it is classified as an energy efficiency intervention. The investment cost for a new dryer is evaluated as high, and can be recovered in a medium period of time. A new dryer has an average likelihood of success or acceptance, and it has the positive point of requiring low corporate involvement.

ARC	Description	Sub-system	Payback Time	Implementation Costs	Amount of Saved Energy	Saving strategy	Activity Type	Ease of Implementation	Likelihood of success/ acceptance	Corporate Involvement	Distance to core processes	Check-up frequency	Indirect effects
2.4221	Install CA intakes in Coolest locations	generation	medium	low	low	efficiency	new installation	dependent	medium	low	distant	one-time	not available
2.4222	Install adequate dryers on CA lines to eliminate blowdown	treatment	medium	high	not available	efficiency	retrofit	dependent	medium	low	distant	one-time	not available
2.4223	Install direct acting units in place of CA in safety system	use	medium	medium	not available	efficiency	new installation	dependent	medium	low	distant	one-time	not available
2.4224	Upgrade controls on compressor	generation	medium	medium	medium	efficiency	retrofit	dependent	medium	low	distant	one-time	proven

2.4225	Install common header on compressor	distribution	medium	high	not available	efficiency	new installation	dependent	medium	low	distant	one-time	not available
2.4226	Use optimum sized compressor	generation	medium/ large	high	low	efficiency	retrofit	dependent	medium	low	distant	one-time	not available
2.4227	Use compressor air filters	treatment	medium	low	low	efficiency	retrofit	easy	medium	low	distant	periodic	proven
2.4231	Reduce the pressure of CA to the minimum required	distribution	short	low	low	efficiency /conservation	optimization	easy	high	low	close/distant	periodic	proven
2.4232	Eliminate CA used for cooling, agitating liquids, moving product, or drying	use	short	medium	high	efficiency	optimization	dependent	medium	wide	close	periodic	proven

2.4233	Eliminate the use of CA	use	short	medium	high	efficiency /conservation	optimization	dependent	medium	wide	close/distant	one-time	proven
2.4234	Cool CA intake with heat exchanger	generation	medium	medium	low	efficiency	new installation	difficult	high	low	distant	one-time	not available
2.4235	Remove or close off unneeded CA lines	distribution	short	medium	not available	efficiency /conservation	optimization	dependent	medium	low	close/distant	periodic	proven
2.4236	Eliminate leaks in in CA lines / valves	distribution	short	low	high	efficiency	procedure	easy	high	wide	close/distant	periodic	not available
2.4237	Substitute CA cooling with water or air cooling	use	short	medium	not available	efficiency	new installation	dependent	medium	low	distant	one-time	not available
2.4238	Do not use CA for personal cooling	use	short	low	not available	efficiency /conservation	procedure	easy	high	wide	close/distant	periodic	not available

Table 6 - Characterization of the energy efficiency interventions. Adapted from (Trianni et al. 2014)

CHAPTER 4 - ANALYSIS OF THE IAC DATABASE

The present chapter is dedicated to the presentation of the main findings from the descriptive statistical analyses of the data included in the IAC database. The chapter is organised as follows: section 4.1 will summarise the basic information about the set-up of the analysis; section 4.2 will compare the number of recommendations and implementation rate in the compressed air and in other technologies; paragraph 4.3 will be dedicated to the temporal trends of the interventions; section 4.4 will provide a general presentation of the EEMs in terms of implementation and economics; sections 4.5, 4.6 and 4.7 will perform a comparison across the levels of some factors, such as company size, energy intensity, and sector.

4.1 Setup of the analysis

The purpose of this section is to introduce the main variables that will be considered throughout the chapter. It is useful to distinguish three main sets of variables. The variables in the first group are the most important, as they are the primary objectives of this study. These are:

- Number of recommendations. It is the total number of times an intervention has been suggested by the IAC centres.
- Implementation percentage. It is the ratio between the number of times an intervention has been undertaken, and the number of times it has been recommended.

The second set of variables of interest includes the economic characteristics of the interventions. They are important to understand which are the “best” interventions according to different dimensions. Considering the quantitative information available in the IAC database, I have decided to analyse the following variables:

- Implementation cost. It is the estimated capital expenditure to undertake the intervention, evaluated in US dollars. I have corrected the implementation costs to the current value of the dollar to eliminate the inflation effect (please refer to Annex A for the discount factors).
- Total annual energy cost savings. It is calculated by summing up the annual cost savings for all the different types of energy sources that the intervention allows to cut. These can be any combination of electricity, natural gas, liquefied petroleum gas (LPG), fuel oil #1 (similar to kerosene), fuel oil #2 (kerosene), fuel oil #4 (a blend of distillate and residual fuel oils), fuel oil #6 (residual fuel oil), coal, wood, and paper. Annual energy cost savings are measured in US dollars per year, and, like the implementation cost, have been actualised to the 2016 value of the dollar.
- Payback time. It is a simple payback time, evaluated in years.

Although redundancy among these factors can be claimed, it must be remembered that the average (or median) value of any of these variables cannot be directly obtained from the other two. Furthermore, they provide at a glance complementary information, as they represent different perspectives in the evaluation of an investment. Another economic attribute that would have been quite interesting to investigate is the Net Present Value of the investment (or, equivalently, the Internal Rate of Return) (Abadie et al., 2012). Unfortunately, it is impossible to calculate the profitability of the interventions from the IAC data, as information on the useful life and eventual operating costs are not available.

The third set of variables are the independent variables. These include time and companies' characteristics. Although variabilities over the years are expected, I have judged that time is not such an interesting factor to deeply discuss. Hence, this will be mainly used as a data-cutting factor. On the other hand, it is worthwhile to assess more carefully the effect of some company characteristics as suggested by several studies in the literature. As mentioned in Chapter 1, the firm characteristics evaluated are:

- Size. It is evaluated according to the number of employees. With respect to the company dimension, samples have been clustered into four levels, such as:
  - ✓ Small (S). They include companies with 10-49 employees;
  - ✓ Medium-size (M). They include companies with 50-99 employees;
  - ✓ Medium-large (ML). They include companies with 100-249 employees; and
  - ✓ Large (L). They include companies more than 250 employees.

- Energy intensity. It is evaluated by the ratio between the yearly energy consumption costs and annual revenues of the company. With respect to the energy intensity of the firm, samples have been clustered into two levels:
  - ✓ Non-energy intensive (ratio < 3%); and
  - ✓ Energy intensive (ratio ≥ 3%).
- Industrial sector. It is evaluated using the ISIC (International Standard Industrial Classification of All Economic Activities) code. The first two digit numbers of the code identify the industrial sector. Manufacturing sectors range between 10 and 33. Thus, with respect to the industrial branch, samples have been clustered into 23 levels, such as:
  - ✓ 10 - Manufacture of food products;
  - ✓ 11 - Manufacture of beverages;
  - ✓ 12 - Manufacture of tobacco products;
  - ✓ 13 - Manufacture of textiles;
  - ✓ 14 - Manufacture of wearing apparel;
  - ✓ 15 - Manufacture of leather and related products;
  - ✓ 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials;
  - ✓ 17 - Manufacture of paper and paper products;
  - ✓ 18 - Printing and reproduction of recorded media,
  - ✓ 19 - Manufacture of coke and refined petroleum products;
  - ✓ 20 - Manufacture of chemicals and chemical products;
  - ✓ 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations;
  - ✓ 22 - Manufacture of rubber and plastics products;
  - ✓ 23 - Manufacture of other non-metallic mineral products;
  - ✓ 24 - Manufacture of basic metals;
  - ✓ 25 - Manufacture of fabricated metal products, except machinery and equipment;
  - ✓ 26 - Manufacture of computer, electronic and optical products;
  - ✓ 27 - Manufacture of electrical equipment;
  - ✓ 28 - Manufacture of machinery and equipment (n. e. c.);
  - ✓ 29 - Manufacture of motor vehicles, trailers, and semi-trailers;
  - ✓ 30 - Manufacture of other transport equipment;
  - ✓ 31 - Manufacture of furniture;
  - ✓ 32 - Other manufacturing; and

✓ 33 - Repair and installation of machinery and equipment.

In conclusion of this section, I report the clustering of the interventions explained in Chapter 3, and the legend of their ARC code, as a reference for the chapter.

		INTERVENTION TYPE	
		HARDWARE	**OPERATION/MAINTENANCE**
TARGETED SUB-SYSTEM	**GENERATION**	2.4221 INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS 2.4226 USE / PURCHASE OPTIMUM SIZED COMPRESSOR 2.4224 UPGRADE CONTROLS ON COMPRESSORS 2.2434 RECOVER HEAT FROM AIR COMPRESSOR	2.4234 COOL COMPRESSOR AIR INTAKE WITH HEAT EXCHANGER
	TREATMENT	2.4227 USE COMPRESSOR AIR FILTERS 2.4222 INSTALL ADEQUATE DRYERS ON AIR LINES TO ELIMINATE BLOWDOWN 2.2435 RECOVER HEAT FROM COMPRESSED AIR DRYERS	
	DISTRIBUTION	2.4225 INSTALL COMMON HEADER ON COMPRESSORS	2.4236 ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES 2.4235 REMOVE OR CLOSE OFF UNNEEDED COMPRESSED AIR LINES 2.4231 REDUCE THE PRESSURE OF COMPRESSED AIR TO THE MINIMUM REQUIRED
	END-USE	2.4223 INSTALL DIRECT ACTING UNITS IN PLACE OF COMPRESSED AIR PRESSURE SYSTEM IN SAFETY SYSTEM	2.4233 ELIMINATE PERMANENTLY THE USE OF COMPRESSED AIR 2.4232 ELIMINATE OR REDUCE COMPRESSED AIR USED FOR COOLING, AGITATING LIQUIDS, MOVING PRODUCT, OR DRYING

			2.4237 SUBSTITUTE COMPRESSED AIR COOLING WITH WATER OR AIR COOLING 2.4238 DO NOT USE COMPRESSED AIR FOR PERSONAL COOLING

Table 7 - Legend of the ARC code of the interventions and clustering

4.2 Comparison with other technologies

As an introductory paragraph, it is interesting to see how compressed air performs with respect to the other technologies. This allows to see which technology areas hide the largest energy efficiency potential, and which ones are more exploited. Table 8 and Figure 47 indicate the number of recommendations and the implementation rate of the energy efficiency interventions for the eight major technologies. These together count 107.876 recommendations, which is about 90 percent of the total number of recommendations in the energy management area (ARC code 2). Such technologies are:

- Furnaces, ovens, and directly fired operations (ARC code 2.11);
- Boilers (ARC code 2.12);
- Electric motors (ARC code 2.41);
- Compressed air: it includes both air compressors (2.42) and heat recovery from air compressors (2.2434);
- Lighting (2.71);
- Space conditioning (2.72);
- Ventilation (2.73);
- Building envelope (2.74).

	TECHNOLOGY			
	2.11 FURNACES, OVENS	**2.12 BOILERS**	**2.41 ELECTRIC MOTORS**	**2.42 COMPRESSED AIR**
NUM RECC	1438	4021	14216	24289
% IMP	50%	57%	54%	60%

	TECHNOLOGY			
	2.71 LIGHTING	**2.72 SPACE CONDITIONING**	**2.73 VENTILATION**	**2.74 BUILDING ENVELOPE**
NUM RECC	28013	7577	884	3149
% IMP	52%	45%	44%	46%

Table 8 - Number of recommendations and implementation rate for the major technologies

As it can be seen, compressed air is the second most addressed technology area with 24.289 recommendations, second only to lighting (28.013 recommendations). Behind air compressors there are the electric motors, which count 14.216 recommendations, which is less than 60 percent of the number of recommendations for the compressed air. This is a quite surprising datum: even though it can be reasonably expected that electric motors are more widespread than air compressors, the number of inefficiencies found during the IAC assessments is greatly larger in the compressed air systems. The remaining five technologies, such as furnaces, ovens, and directly fired operations (2.11), boilers (2.12), space conditioning (2.72), ventilation (2.73), and building envelope (2.74), cover 14 percent of the total number of recommendations.

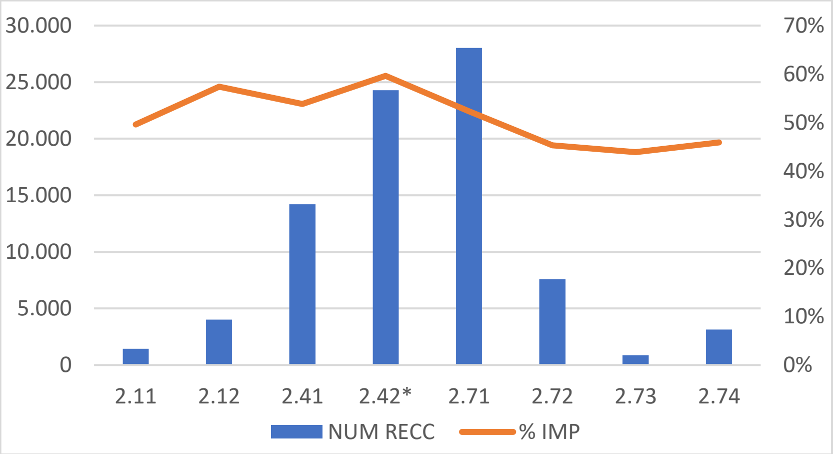


Figure 47 - Number of recommendations and implementation rate for the major technologies

In regard with the implementation percentage, it can be noted that air compressor is the most implemented technology, with 60 percent of IAC suggestions undertaken. This points out that interventions for improving the energy efficiency of the compressed air systems are considered attractive by US manufacturing companies, or at least more attractive than the interventions in the other systems. Also, the adoption frequency of the interventions for improving the energy efficiency level of the boilers is remarkably above the grand average (51 percent), and it is equal to 57 percent. On the other extreme of the scale, the worst performing technologies are ventilation and space conditioning, which are characterized by implementation rates as low as 44 and 45 percent respectively.

4.3 Time series

This section analyses the time series of the implementation of the interventions for the compressed air. The first purpose is to examine whether manufacturers have become more inclined to energy efficiency over the years, or if their attitude has not changed. As stated before, this analysis will allow to cut part of the IAC data from successive analyses. The results are reported with an increasing level of detail. First, it is presented an analysis of the data for all the energy efficiency interventions in the compressed air aggregated together. Then, the focus will shift to the eight (seven non-empty) clusters of EEMs.

4.3.1 All interventions

Let us start with a broad overview on the entire compressed air system. Table 9 and Figure 48 display the trends of the aggregate number of recommendations and the overall implementation rate for the seventeen energy efficiency interventions, between 1981 and 2016. In the last columns of the table below are also reported the total number of recommendations implemented, given by the product of the previous two variables.

YEAR	NUM REC	% IMP	NUM IMP
1981	7	29%	2
1982	143	32%	46
1983	99	38%	38
1984	182	68%	123
1985	335	69%	231
1986	243	73%	178
1987	238	73%	174
1988	289	75%	217
1989	254	65%	166
1990	300	69%	206
1991	383	58%	224
1992	508	55%	277
1999	818	56%	456
2000	827	52%	426
2001	749	55%	414
2002	797	60%	480
2003	930	55%	507
2004	1076	61%	656
2005	989	54%	536
2006	832	55%	456
2007	654	57%	373
2008	706	54%	384
2009	588	56%	328
2010	692	53%	370

1993	620	56%	345
1994	815	55%	452
1995	1041	60%	623
1996	968	61%	592
1997	746	56%	418
1998	757	58%	436
2011	691	54%	373
2012	873	51%	447
2013	889	58%	516
2014	829	54%	446
2015	932	49%	453
2016	400	48%	190

Table 9 - Time series of the number of recommendations and implementation rate of all interventions

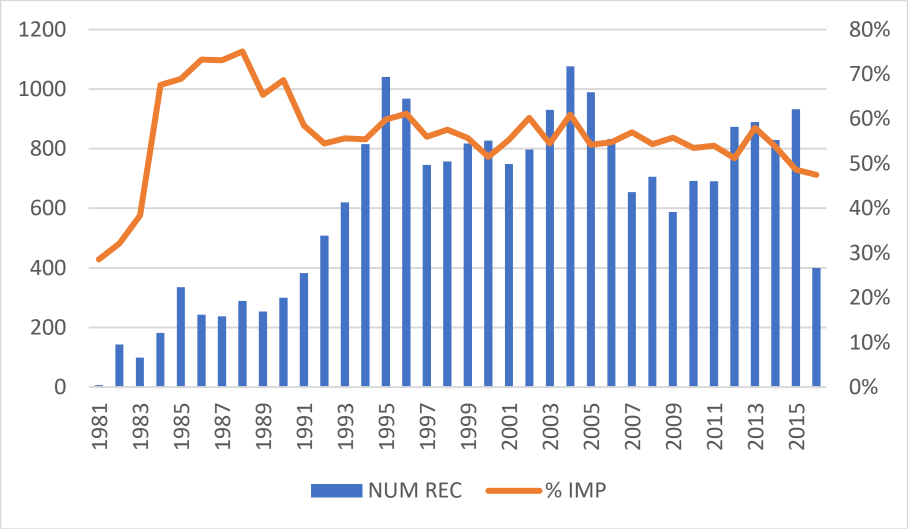


Figure 48 - Time series of the number of recommendations and implementation rate of all interventions

The data point out that there is an initial transient period during which the IAC program was earning an increasing popularity among US manufacturers. In fact, in the timeframe between 1981 and 1993 there is a continuous rise of the number of recommendations, which grows from 7 in 1981 to 620 in 1993. In 1994, the number of recommendations was 815, closer to the average value of the subsequent years. Similar considerations hold also for the implementation rate, that quickly rose during the initial years. After a peak of 75 percent in 1988, it later decreased to stabilise in the range of 50 - 60 percent. Overall, it seems that the transient effect can be considered finished in 1994.

Better discussing the data since 1994, the alternating trend of the amount of IAC suggestions may be interpreted as a variable involvement of the US manufacturers with the IAC program. Of course, the discussion here is limited to the energy efficiency of compressed air systems only. The more significant drop occurred in the years right after the 2007, suggesting a potential effect of the financial crisis. However, the same trend cannot be observed for the implementation frequency. In this sense, one may say that the companies that contacted the IAC centres eventually implemented a similar fraction of suggestions of the previous years.

At this introductory point the level of analysis is extremely aggregate, so no precise conclusions can be drawn. However, it seems that, despite the combined efforts of governmental entities, research and industry, manufacturing companies reject investments in energy efficiency today as much as they did in the past. Nevertheless, it must be said that it is difficult to univocally interpret the data, as this would require a profound historical knowledge of several elements, such as IAC program, US economic scenario, and technological improvements.

4.3.2 Clusters of interventions

It is interesting to zoom the level of detail, to see whether some differences exist in the time trends of the groups of interventions, or if they have been implemented in a similar way. To do so, I have considered the number of recommendations implemented, combining the effect of the number of recommendations advanced by the IAC personnel, and the implementation rate of the companies. In this way, even though results are more aggregate, a synthetic and comprehensive overview can be outlined. With this purpose, Table 10 presents the number of recommendations implemented year by year, for each of the seven clusters. The time series for the three most implemented clusters are highlighted in green, and displayed in Figure 49.

	NUMBER OF IMPLEMENTATIONS						
YEAR	**GEN-HARD**	**GEN-OP**	**DIS-HARD**	**DIS-OP**	**TREAT-HARD**	**USE-HARD**	**USE-OP**
1981	2	0	0	0	0	0	0
1982	19	0	0	26	0	0	1
1983	14	0	0	22	0	0	2
1984	36	0	0	82	0	0	5
1985	73	0	0	144	11	0	3
1986	52	0	0	118	2	0	6
1987	71	0	0	97	1	0	5
1988	73	0	0	130	2	0	12
1989	59	0	0	100	1	0	6
1990	75	0	0	120	2	0	9
1991	89	0	0	115	3	0	17
1992	101	1	0	143	3	0	29
1993	124	0	0	211	1	1	8
1994	160	0	0	283	1	0	8
1995	220	0	0	377	3	0	23
1996	214	2	0	334	1	1	40
1997	140	0	0	257	0	0	21
1998	167	2	0	248	1	0	18
1999	155	0	1	279	3	1	17

2000	107	1	0	296	2	0	20
2001	95	2	0	303	3	1	10
2002	114	0	1	337	0	1	27
2003	82	1	1	377	3	0	43
2004	120	1	1	475	9	1	49
2005	107	3	2	364	5	1	54
2006	107	3	1	316	2	2	25
2007	74	1	1	266	3	1	27
2008	65	1	2	281	2	0	33
2009	61	1	1	250	3	1	11
2010	85	0	0	264	2	1	18
2011	71	2	1	276	4	0	19
2012	84	0	0	335	2	1	25
2013	111	0	1	361	4	1	38
2014	83	1	2	316	3	0	41
2015	88	0	2	304	2	0	57
2016	30	0	0	146	0	1	13
TOT	3328	22	17	8353	84	15	740

Table 10 - Time series of the number of implementations of the clusters

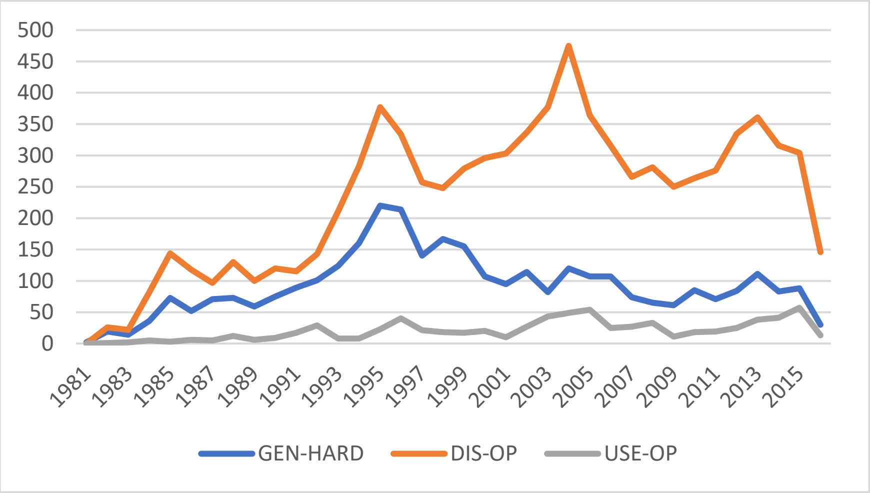


Figure 49 - Time series of the number of implementations of the three main clusters

The hardware investments improving the energy efficiency of the generation group (compressor and control) have been quite frequently undertaken by the US manufacturers. Looking at the overall time series since 1981, it can be noted the same initial transient which characterises also the entire compressed air. Considering the data since 1994, the number of implementations oscillates between 30 in 2016 and 220 in 1995. It can be observed also a significant drop in the number of implementations since the year 2007, which slowly and intermittently increased again from 2010.

The operation - distribution cluster includes all the operational EEMs that can potentially act all over the distribution network, from the compressors' room to the location of the end-use equipment. This cluster has been by far the most implemented year after year. Excluding the transient years, the implementation number ranges between 146 in 2016 and 475 in 2004. Overall, the oscillations for this group are significant. If we compare Figure 48 and Figure 49, it is easy to note a remarkable similarity between the time trend of the number of recommendations for whole compressed air system (blue bars), and the trend of the number of operational interventions implemented in the distribution network (orange line).

The end-use-operation cluster (which includes the four interventions related to the misuses of the compressed air which can be targeted with operative interventions) shows some differences over the years. The lowest number of implementations occurred in 1994 (8), while the maximum in 2015 (57). The implementations suddenly dropped in 2006 first, and then again in 2009, to later increase since 2012. Also for this cluster, an initial transient can be observed.

The analyses of this section indicate the existence of an initial transient period during which the number of IAC recommendations was steadily increasing. In order to eliminate potential transient effects, the analyses of the subsequent sections will consider only the data collected since 1994. A secondary benefit of this choice is that the successive statistics will be more representative of the current situation.

4.4 Presentation of the interventions

This section is set out to clearly present the objects of the study, i.e. the interventions to improve the efficiency of a compressed air system. Sub-section 4.4.1 addresses the groups of interventions, whereas sub-section 4.4.2 deals with the interventions individually. Both the groups and the specific EEMs are presented in terms of number of recommendations, implementation rate, implementation cost, energy savings, and payback time.

4.4.1 Clusters of interventions

The table below synthetically indicates the number of recommendations and the implementation rate for each of the seven clusters, sorted by decreasing number of suggestions. The three most recommended clusters are highlighted in green. The data are also plotted in Figure 50.

CLUSTER	NUM REC	% IMP
DIS - OP	10768	66%
GEN - HAR	6599	39%
USE - OP	1568	41%
TR - HAR	129	45%
DIS - HAR	52	33%
GEN - OP	48	44%
USE - HAR	26	54%
TOT/AVG	19190	54%

Table 11 - Number of recommendations and implementation rate of the clusters

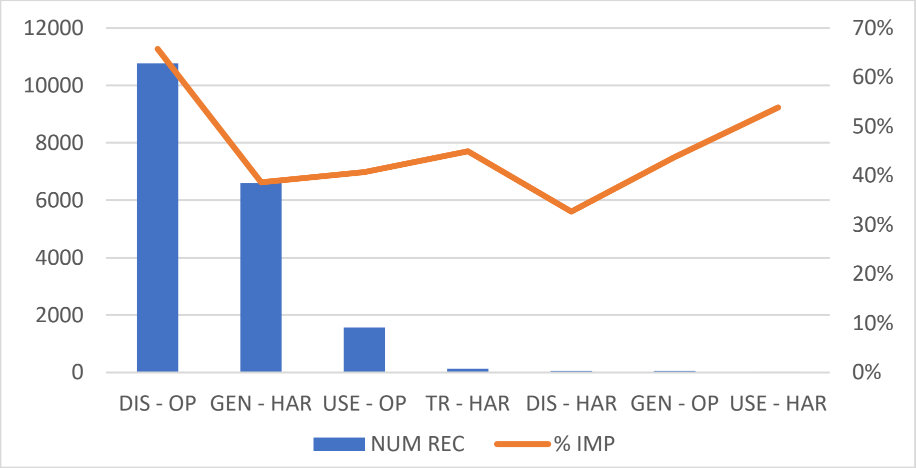


Figure 50 - Number of recommendations and implementation rate of the clusters

The number of recommendations column clearly indicates that the IAC staff has mostly found operational inefficiencies in the distribution networks of the assessed compressed air systems (more than 10.700). The implementation frequency of the distribution's recommendations is also the highest, equal to 66 percent. The second most targeted sub-system is the compressed air generation, with about 6.600 hardware-type suggestions. On the other hand, its implementation rate is quite low (39 percent), suggesting that manufacturers are relatively unwilling to undertake machine/equipment investments for the compressed air generation. Only slightly more adopted are the operational-type EEMs targeting the final misuses of compressed air, implemented 41 percent of the time, and recommended around 1.570 times. As mentioned in the time-analysis section, the remaining four clusters (generation-operation, treatment-hardware, distribution-hardware, use-hardware), have a very marginal contribution, equal to 1,3 percent of the overall number of recommendations. For this reason, they will be largely neglected in the following discussions.

Let us now consider the economics of the EEMs groups. Considering the dispersion of the data, I have eventually decided to carry out the economic characterisation of both clusters and individual interventions using the medians (rather than the averages) as punctual indicators of the economic variables. The reason is that this indicator seems to be more representative of the majority of the samples, because it is less sensitive than the average to the few extreme values (potential outliers), and it is intrinsically able to mitigate the effect of the tails of a distribution. This approach has been used also by (Trianni 2012). Table 12 below indicates for each of the seven clusters the median values of the implementation cost, energy cost savings, and payback time. The three most recommended clusters are highlighted in green. The bubble plot in Figure 51 is helpful to visualise the data at glance, with each cluster represented by a bubble, whose size suggests the payback time (the larger the size, the longer the payback time). The horizontal coordinate indicates the implementation cost, whereas the vertical the energy cost savings. It can be imagined splitting the plot area into four quadrants.

CLUSTER	IMP COST [USD 2016]	EN SAV [USD 2016/YEAR]	PBT [YEARS]
DIS – OP	519	2638	0,18
GEN – HARD	1092	2131	0,59
USE – OP	1876	3429	0,50
TREAT – HARD	1697	3656	0,52
DIS – HARD	4287	4761	0,76
GEN – OP	2494	3092	0,92
USE – HARD	2033	2597	0,42

Table 12 - Median economic parameters of the clusters

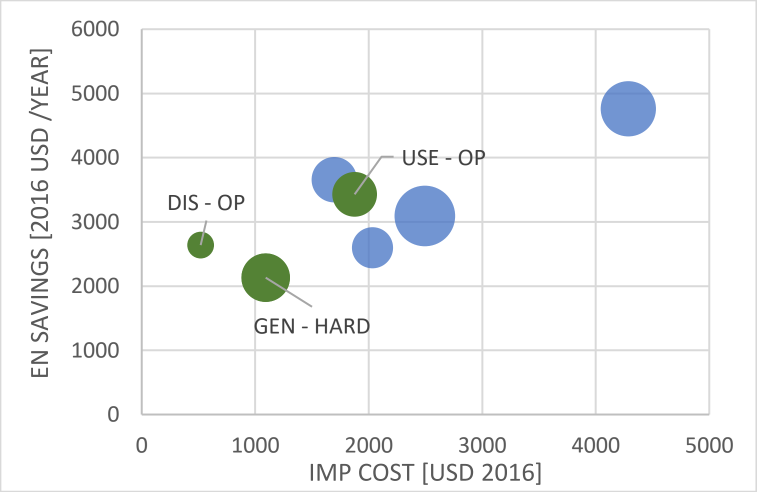


Figure 51 - Bubble plot of the median economic parameters of the clusters

The distribution-operation cluster is by far the most cost - effective one. In fact, not only the median implementation cost is significantly lower than the other groups (about 520 dollars), yet also its energy savings are not negligible (around 2.640 dollars/year). Surprisingly, the median energy cost savings achievable with operative practices along the distribution system are higher than those stemming from hardware investments in the generation group. Overall, the exceptional economic attributes that characterise the distribution-operation cluster (including a median payback time of about 2 months) seem to justify its (relatively) high implementation rate. These results just go to show that energy efficiency is not only a matter of expansive equipment investments, and that the contribution of good energy management practices cannot be overlooked if the full energy efficiency potential is to be exploited.

4.4.2 Single interventions

Let us start from the analysis of the data about the recommendation and the implementation. Table 13 and Figure 52 show the number of recommendations, and the implementation rate of the interventions, sorted by decreasing number of recommendations. In the table, the results of the seven most recommended EEMs are highlighted in green.

The frequency distribution of the recommendations is extremely uneven, and it ranges between 6.783 and 13 recommendations. The implementation rate is also highly variable, and it ranges between 77 and 8 percent. The absence of trends of the orange line points out that the implementation rate and the number of recommendations are independent. Even if an intervention has many recommendations, it does not necessarily mean that it also has a high implementation rate. Even though this may be trivial, it is important to be highlighted. In effect, it would be desirable to see a high implementation frequency for an intervention recommended thousands of times, rather than for an intervention suggested only a few times.

ARC	**2,4236**	**2,4231**	**2,4221**	**2,2434**	**2,4232**	**2,4226**	**2,4224**	**2,4233**	**2,4235**
NUM REC	6783	3853	3767	1526	1306	675	631	197	132
% IMP	77%	47%	41%	30%	41%	41%	41%	37%	58%

ARC	**2,4222**	**2,4225**	**2,4234**	**2,4227**	**2,4237**	**2,4238**	**2,4223**	**2,2435**	**TOT/AVG**
NUM REC	75	52	48	41	34	31	26	13	19190
% IMP	48%	33%	44%	51%	47%	55%	54%	8%	54%

Table 13 - Number of recommendations and implementation rate of the interventions

The IAC centres have mostly recommended seven types of interventions, that together hold a share of 97 percent of the total number of recommendations. *Eliminate leaks in inert gas and compressed* *air lines/ valves* (2.4236) largely stands over the other EEMs. It has been recommended more than 6.700 times, and by itself covers 35 percent of the total set of recommendations. Remarkably, its implementation rate is also the highest one, equal to 77 percent. In second and third positions, there are *Reduce the pressure of compressed air to the minimum required* (2.4231), and *Install compressor air intakes in coolest locations* (2.4221) which represent 20 percent of the total recommendations each. Their implementation rates are 47 and 41 percent respectively. Descending along the ranking we find *Recover heat from air compressor* (2.2434). With a share of 8 percent, it is implemented as low as 30 percent of the times it is suggested. In fifth position, *Eliminate or reduce compressed air used for cooling, agitating liquids, moving product, or drying* (2.4232), which represents 7 percent of the recommendations and has been implemented 41 percent of the times. Finally, *Use / purchase optimum sized compressor* (2.4226), and *Upgrade controls on compressors* (2.4224) have a share of 4 and 3 percent each, and both have implementation rates of 41 percent.

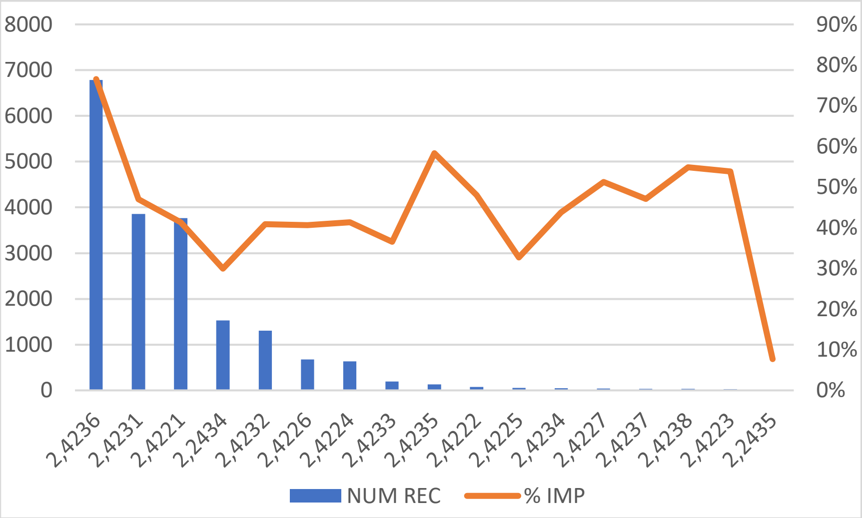


Figure 52 - Number of recommendations and implementation rate of the interventions

The recommendations of the remaining ten interventions sum up to as low as 3 percent. There may be several reasons why these EEMs have been so scarcely addressed by the IAC staff. The simplest is that the inefficiencies they target have been rarely encountered during the assessments. This may explain why intervention 2.4238 (*Do not use compressed air for personal cooling*) has been recommended only 31 times. Also, it is possible that the targeted inefficiency can be eliminated in a more cost-effective way. For example, both intervention 2.4234 (*Cool compressor air intake with heat exchanger*) and 2.4221 (*Install compressor air intakes in coolest locations*) aim at securing that the air at the compressor inlet is as cool as possible. However, if the latter has been recommended about 3.800 times, the former counts nearly 50 recommendations, showing that it is by far the second choice.

Whatever the reason these EEMs are overlooked by the IAC centres, their contribution to the overall energy efficiency of compressed air is minor. The pie chart in Figure 53 shows the breakdown of the energy efficiency potential in the compressed air among the interventions. The contribution of each intervention is calculated as the ratio between the energy savings associated with all the recommendations of the intervention, and the total energy savings. Energy savings refer to the recommendations both implemented and non-implemented, and are evaluated in actualised US dollars.

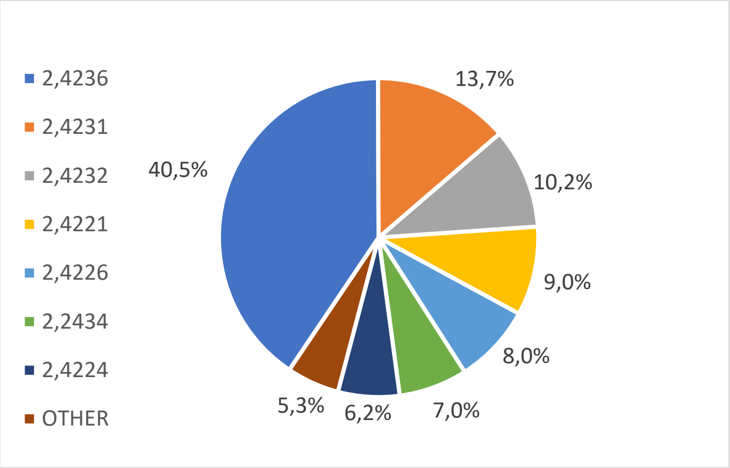


Figure 53 - Decomposition of the energy efficiency potential

The graph shows that if all the recommendations associated with the ten least-recommended interventions were implemented, the energy efficiency gap would close of 5,3 percent. On the other hand, the vast majority of the energy efficiency gap is attributable to compressed air leaks, which cover the lion share with 40,5 percent. The remaining 54,2 percent is distributed among the other six most recommended interventions as follows:

2.4231 - Reduce the pressure of compressed air to the minimum required: 13,7%.

2.4232 - Eliminate or reduce compressed air used for cooling, agitating liquids, moving product, or drying: 10,2 %.

2.4221 - Install compressor air intakes in coolest locations: 9,0%.

2.4226 - Use / purchase optimum sized compressor: 8,0%.

2.2434 - Recover heat from air compressor: 7,0%.

2.4224 - Upgrade controls on compressors: 6,2%.

After having addressed the frequency of recommendation and the implementation rate of the interventions, we can now move to their economic performances. The table below summarises the median values of the implementation cost, energy cost savings, and payback time of the interventions, which are also plotted in Figure 54.

ARC	IMP COST [USD 2016]	EN COST SAV [USD 2016/YEAR]	PBT [YEARS]
2,4236	695	3206	0,20
2,4231	81	1945	0,07
2,4221	678	1293	0,52
2,2434	1998	3267	0,67
2,4232	1628	3389	0,43
2,4226	8722	7403	1,13
2,4224	6913	7988	0,65
2,4233	3620	4273	0,88
2,4235	1240	2201	0,31
2,4222	4052	4412	0,74
2,4225	4287	4761	0,76
2,4234	2494	3092	0,92
2,4227	772	2969	0,24
2,4237	2345	3650	0,76
2,4238	1557	2070	0,51
2,4223	2033	2597	0,42
2,2435	4452	3247	0,71

Table 14 - Median economic parameters of the interventions

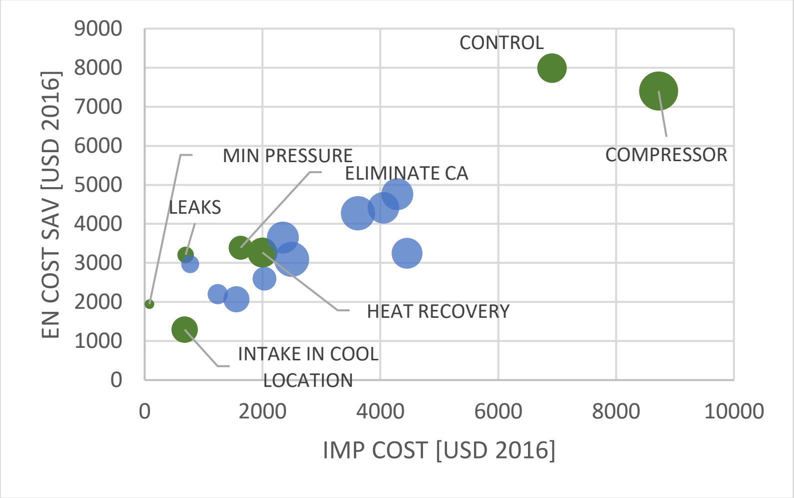


Figure 54 - Bubble plot of the median economic parameters of the EEMs

Fifteen out of the seventeen EEMs are in the bottom-left quadrant, with median investment costs between 80 and 4.450 dollars, and median energy savings between 680 and 4.800 dollars per year. The bubbles in this area seem to be in the around of a diagonal line, indicating that, in general, the more expansive interventions also lead to higher energy savings. However, it is apparent that some interventions, in median terms, economically perform better than others, as they either secure greater savings with similar implementation cost, or require lower upfront investment for comparable energy savings.

It is worth noting that intervention 2.4236 (Eliminate leaks in inert gas and compressed air lines/ valves), with a median implementation cost of less than 700 dollars, leads to more than 3.200 dollars of energy cost saved per year. The result is an advantageous payback time of 2,4 months. It can be noted also that interventions 2.4224 (Upgrade controls on compressors) and 2.4226 (Use / purchase optimum sized compressor) are by far the most expansive EEMs, with median implementation cost of about 8.700 dollars for a new compressor, and 6.900 dollars for an upgraded control system. On the other hand, the energy costs saved are also exceptionally high, equal to 7.400 dollars per year for the compressor, and 7.990 dollars per year for the control. Furthermore, all the interventions except 2.4226 have payback significantly below 1 year, which is a reasonable time for the typical industry investment requirements.

4.5 Comparison by company size

This section investigates if companies of different size have the same attitude towards the energy efficiency of their compressed air systems, or if some differences exist. Sub-section 4.5.1 analyses the number of recommendations and the implementation rate of the clusters, while sub-section 4.5.2 addresses the specific interventions.

4.5.1 Clusters of interventions

The table below indicates the number of recommendations and the implementation rate of the seven groups of interventions, for each company size: small (S), medium-size (M), medium-large (ML), and large (L). I have sorted the clusters by decreasing total number of recommendations, and highlighted the top three.

	NUM REC				% IMP			
CLUSTER	**S**	**M**	**ML**	**L**	**S**	**M**	**ML**	**L**
DIS - OP	1288	4632	2350	2459	69%	65%	66%	65%
GEN - HARD	688	2888	1447	1558	43%	37%	39%	39%
USE - OP	154	624	351	438	39%	42%	40%	40%
TREAT-HARD	16	51	22	40	56%	39%	59%	40%

DIS - HARD	2	22	12	16	0%	36%	42%	25%
GEN - OP	3	16	14	15	33%	44%	43%	47%
USE - HARD	4	12	7	3	25%	58%	43%	100%
TOT/AVG	2155	8245	4203	4529	58%	53%	54%	53%

Table 15 - Number of recommendations and implementation rate of the clusters by company size

First, it can be noted that the number of recommendations to small companies is only 2.155 (11 percent of the total). Now, this relatively low number of recommendations to small companies reflects the low number of assessments they received: only 12 percent of the total number of assessments analysed is related to SEs, with respect to 43 percent for MEs, 22 percent for MLEs, and 23 percent for LEs. This distribution does not correctly represent the US manufacturing landscape, which is largely composed by small enterprises. According to the US Manufacturing Institute at April 2014 as much as 76 percent of the manufacturing companies employed less than 20 employees. The inconsistency between the US distribution and the IAC one can be appreciated in the figures below.

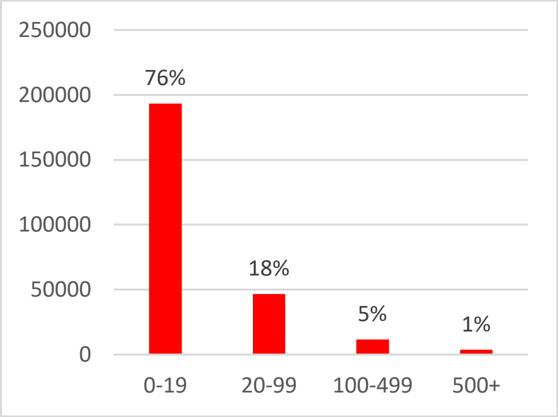


Figure 55 - Distribution of US companies

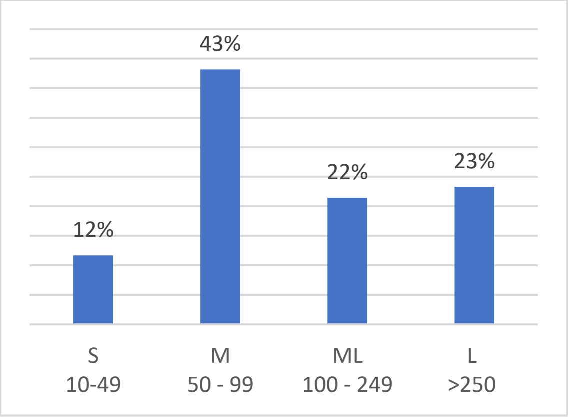


Figure 56 - Distribution of the IAC companies

Let us now move to the number of recommendations of the individual clusters. The ranking of the clusters by number of recommendations is the same for all the company sizes (limiting the discussion to the top-three clusters). This can be noted by the decreasing value of the numbers in the four left-side columns of the table. Thus, the distribution network is always the most targeted part of the plant (operatively), followed by the compressed air generation (hardware investments), then the end-use applications (operatively). As it can be seen, small enterprises received the lowest number of recommendations for each of the four clusters. This consideration is important as at deeper level analysis it can be expected to encounter low number of replicates for some interventions in the small companies.

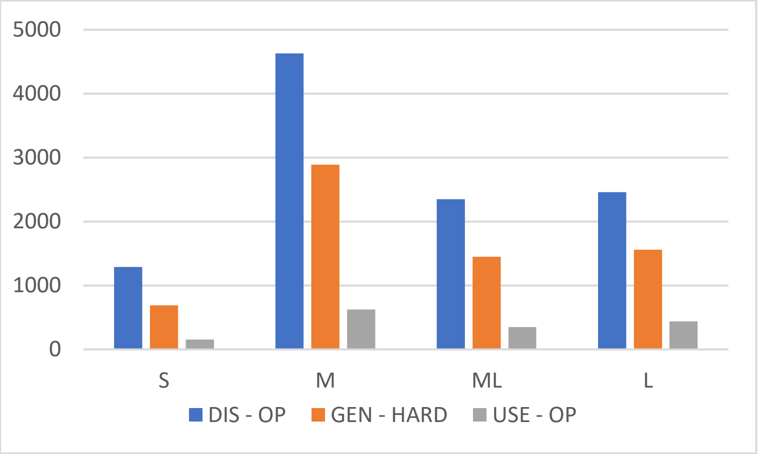


Figure 57 - Number of recommendations of the top clusters by company size

Only few percentage points variations exist in the implementation rate among companies of different size. The implementation frequency of the operative-type EEMs relative to the distribution ranges between 65 and 69 percent, between 37 and 43 percent for the generation, and between 39 and 42 percent for the end-use cluster.

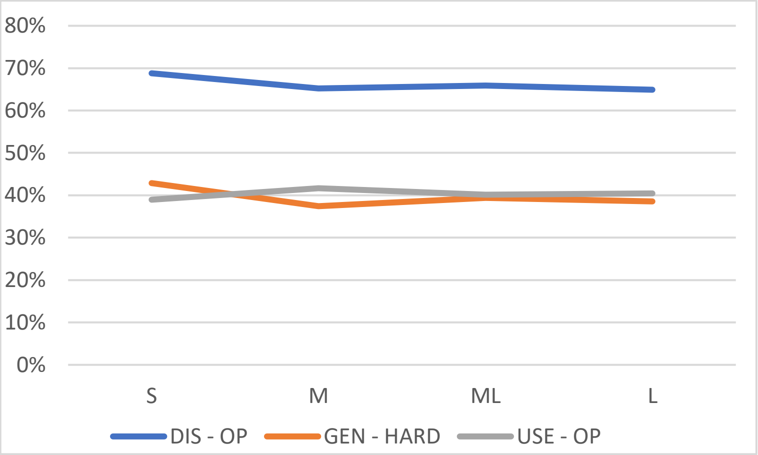


Figure 58 - Implementation rate of the top clusters by company size

4.5.2 Single interventions

Table 16 reports the number of recommendations and the implementation rate of the interventions per each company size. The interventions are sorted by decreasing total number of recommendations, and the top-seven interventions are highlighted in green.

	NUM REC				% IMP			
ARC	**S**	**M**	**ML**	**L**	**S**	**M**	**ML**	**L**
2,4236	791	2886	1484	1593	78%	76%	76%	76%
2,4231	478	1701	830	834	53%	47%	47%	44%
2,4221	389	1704	820	848	44%	39%	42%	43%
2,2434	139	664	347	370	36%	29%	31%	29%
2,4232	123	535	298	350	40%	41%	38%	43%
2,4226	84	292	145	151	46%	40%	41%	39%
2,4224	76	228	135	189	43%	44%	41%	38%
2,4233	22	67	41	66	23%	40%	46%	30%
2,4235	19	45	36	32	79%	56%	58%	50%
2,4222	10	31	11	23	60%	48%	45%	43%
2,4225	2	22	12	16	0%	36%	42%	25%
2,4234	3	16	14	15	33%	44%	43%	47%
2,4227	4	16	8	13	75%	31%	88%	46%
2,4237	5	12	8	9	60%	42%	75%	22%
2,4238	4	10	4	13	75%	70%	50%	38%
2,4223	4	12	7	3	25%	58%	43%	100%
2,2435	2	4	3	4	0%	0%	33%	0%

Table 16 - Number of recommendations and implementation rate of the interventions by company size

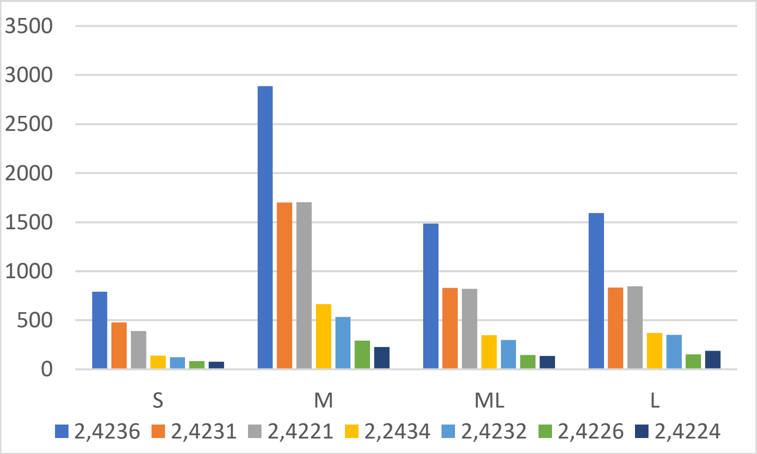


Figure 59 - Number of recommendations of the top interventions by company size

Let us start commenting the results about the number of recommendations. If we read the table by columns, it is easy to realise that the numbers are almost sorted in descending order. In other words, the frequency distributions of the recommendations are fairly similar among the company sizes, as also shown in Figure 59. Remarkably, the top-seven EEMs are the same for any company size, and with almost the same rank order. However, intervention 2.4224 (Upgrade controls on compressors) is more recommended than 2.4226 (Use / purchase optimum sized compressor) to the large companies. It may be assumed that LEs are more likely to have multi-compressor installations, and, thus, they more often require advanced control systems to co-ordinate the individual machines. For smaller companies with one-compressor systems, it may be better to correctly size the compressor, perhaps in conjunction with an adequately large compressed air tank, rather than upgrading the controls.

Let us now focus on the results relative to the implementation rate of the interventions. The table indicates that the implementation frequency is reasonably uniform for the most recommended interventions, whereas, on other hand, large swings can be appreciated over the last ten interventions. For example, intervention 2.4223 (Install direct acting units in place of compressed air pressure system in safety system) has been implemented by 25 percent of SEs, 58 percent of MEs, 43 percent of MLEs and by all LEs that have been suggested to undertake it. However, it must be reminded that this EEM has been recommended only 27 times since 1994. In effect, its large variability is quite meaningless, as the number of samples across the levels is extremely low, and a difference in the implementation of few recommendations leads to large variations in the implementation rate. Figures 59 below shows that no exceptional differences can be pointed out in the implementation rate of the most important interventions.

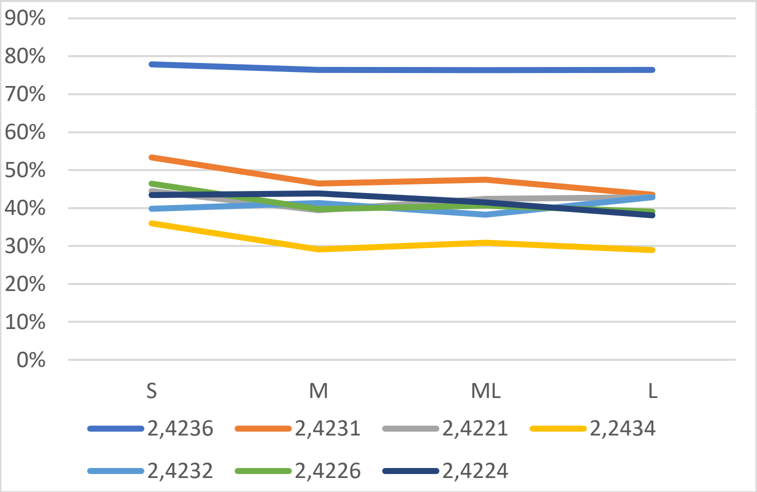


Figure 60 - Implementation rate of the top interventions by company size

4.6 Comparison by energy intensity

This section evaluates if the energy intensity of a company has any effect on the efficiency of its compressed air system. The results are presented in the same way as in the previous section. Thus, paragraph 4.6.1 reports the number of recommendations and the implementation rate of the groups of interventions for the intensive and non-intensive firms, while sub-section 4.6.2 provides a more thorough comparison for the individual interventions.

4.6.1 Clusters of interventions

The table below provides the number of recommendations and the implementation rate of the seven clusters of interventions, distinguishing between non-energy-intensive, and energy-intensive firms. As usual, the clusters are sorted by decreasing number of recommendations and the most recommended clusters are highlighted.

	NUM REC		**% IMP**	
CLUSTER	**NON-INT**	**INT**	**NON-INT**	**INT**
DIS – OP	8707	2007	65%	68%
GEN – HARD	5402	1163	39%	39%
USE – OP	1235	323	42%	38%
TREAT – HARD	92	37	47%	41%
DIS – HARD	45	7	33%	29%
GEN – OP	34	13	41%	46%
USE – HARD	17	9	47%	67%
TOT/AVG	15532	3559	54%	55%

Table 17 - Number of recommendations and implementation rate of the clusters by energy intensity

The total number of recommendations to the non-intensive companies is remarkably higher than the one to the intensive companies, covering around 80 percent of the total set of recommendations. In this case, the distribution of the companies assessed by the IAC (82 percent non-intensive and 18 percent intensive) roughly reflects the industrial scenario, which is largely composed by non-intensive companies.

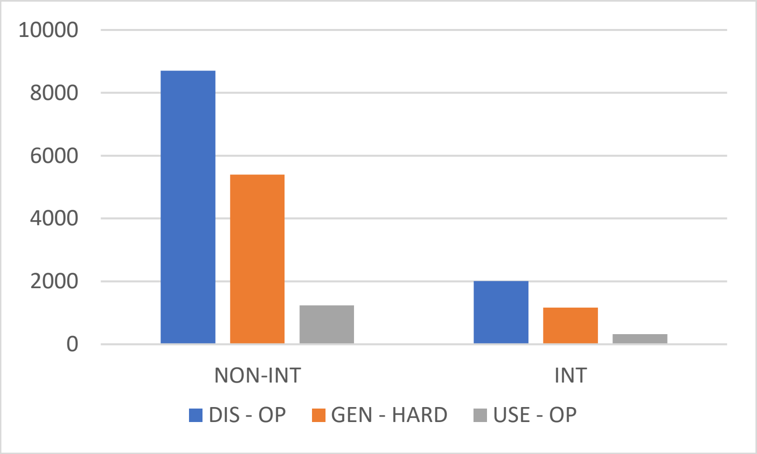


Figure 59 - Number of recommendations of the top clusters by energy intensity

In regard with the top three clusters, their ranking in terms of number of recommendations is equal for both types of companies. The operative inefficiencies in the distribution system are always the most numerous, followed by the hardware ones in the generation group, then the operative-type inefficiencies related to the end-use of compressed air.

About the adoption of the interventions, only few percentages of difference can be pointed out in two of the top three clusters. If non-intensive companies are tiny more willing to undertake the suggestions in the operative-use cluster (4 percent more often), energy intensive have very slightly higher implementation rate in the distribution-operation one (3 percent higher). Absolutely no differences instead can be pointed out in the generation group.

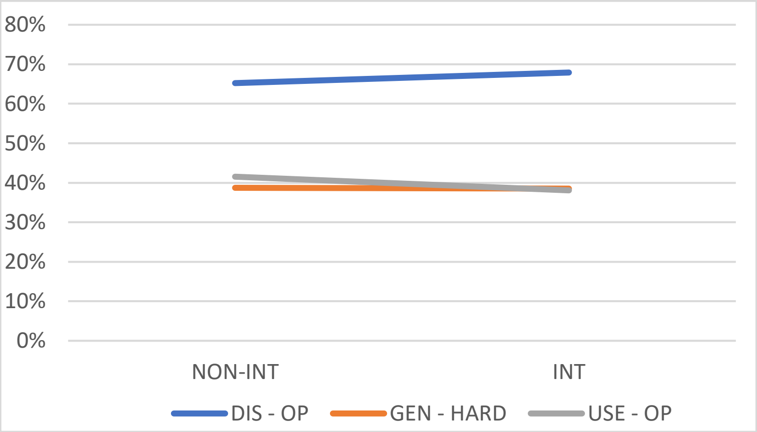


Figure 60 – Implementation rate of the top clusters by energy intensity

4.6.2 Single interventions

Table 18 indicates the number of recommendations, and the implementation rates of the interventions, distinguishing between non-intensive and intensive companies. As usual, the interventions are sorted by decreasing number of recommendations they have received overall. The first seven rows, representing the most recommended and highest potential interventions, are highlighted in green.

	NUM REC		% IMP	
ARC	**NON-INT**	**INT**	**NON-INT**	**INT**
2,4236	5486	1264	76%	78%
2,4231	3120	712	46%	51%
2,4221	3115	634	41%	43%
2,2434	1270	247	31%	26%
2,4232	1032	267	42%	38%

2,4226	533	138	41%	41%
2,4224	484	144	42%	40%
2,4233	148	47	37%	36%
2,4235	101	31	56%	65%
2,4222	56	19	50%	42%
2,4225	45	7	33%	29%
2,4234	34	13	41%	46%
2,4237	30	4	47%	50%
2,4227	27	14	56%	43%
2,4238	25	5	56%	40%
2,4223	17	9	47%	67%
2,2435	9	4	0%	25%

Table 18 - Number of recommendations and implementation rate of the interventions by energy intensity

Let us start discussing the number of recommendations. As mentioned in the previous paragraph, the IAC recommendations are extremely concentrated in the non-energy-intensive clusters. As expectable, this holds also for the individual interventions. If we look how the recommendations are distributed among the interventions for each of the two types of company, it can be said that the distributions are, overall, comparable. Only two minor differences in the rankings can be appreciated in the first interventions:

- Intervention 2.4232 (Eliminate or reduce compressed air used for cooling, agitating liquids, moving product, or drying) has been more frequently recommended than 2.2434 (Recover heat from air compressor) to the energy-intensive companies.
- Intervention 2.4224 (Upgrade controls on compressors) has been slightly more frequently recommended than 2.4226 (Use / purchase optimum sized compressor), always to the energy-intensive companies.

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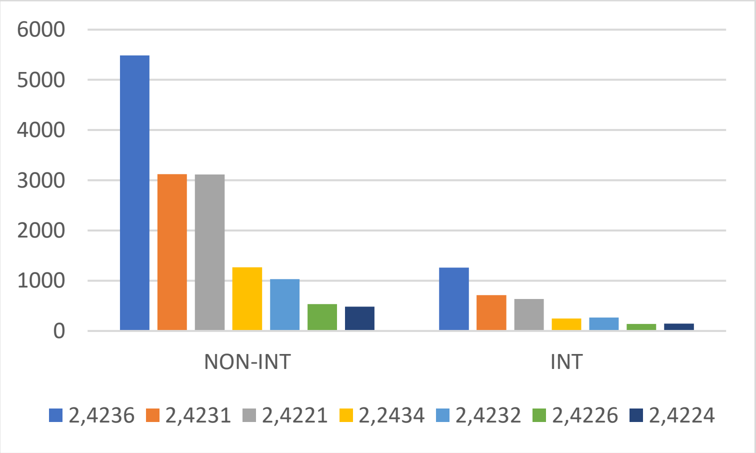

Figure 61 - Number of recommendations of the top interventions by energy intensity

Let us consider the implementation rate of the most-recommended interventions (Figure 62). Intervention 2.4236 (Eliminate leaks in inert gas and compressed air lines/ valves) is, as always, the most implemented EEM (76– 78 percent of the times it is suggested). For the others, virtually no variability exists, except than for a 5 percent for 2.4231 (Reduce the pressure of compressed air to the minimum required), and 2.2434 (Recover heat from air compressor).

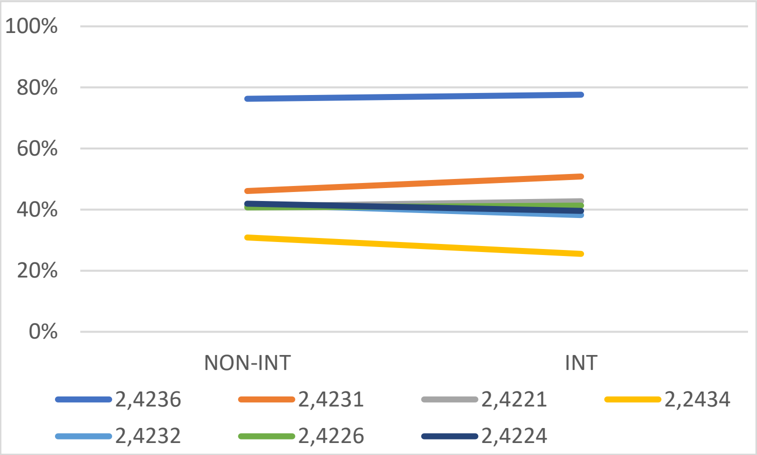

Figure 62 – Implementation rate of the top interventions by energy intensity

4.7 Comparison by sector

This section proposes a comparison among enterprises of different manufacturing branches. The purpose is to understand if manufacturing companies implement energy efficiency interventions to the same extent, or if differences exist throughout the industries. The order in which the findings are presented is specular to the one adopted for the size and for the energy-intensity. Hence, paragraph 4.7.1 reports the results at cluster level, while sub-section 4.7.2 provides the more detailed analyses for the single interventions.

4.7.1 Clusters of interventions

Table 19 in the next page reports the number of recommendations received in the seven clusters by the 24 different manufacturing branches, identified with the corresponding ISIC codes. The clusters and the sectors are sorted by decreasing total number of recommendations.

Before addressing the commonalities and the differences for the single clusters, it is convenient to consider the total number of recommendations of the sectors, as indicated in the last column of the table. As for the company size and energy intensity, also for the sector the distribution of the samples in the database is highly unequal. However, if in the previous cases the few levels allowed to perform complete analyses, the situation for the sector is more critical.

In fact, the number of samples associated to some sectors is extremely low, so that no analysis can be made, not even at cluster level. Sector 33 (Repair and installation of machinery and equipment) is the most extreme example, with only one recommendation overall. This branch, as well as other ones, will be inevitably excluded from the successive analyses. For this reason, in the table are highlighted 24 cells, corresponding to the 3 most recommended clusters (a usual) and to the 8 sectors with the highest number of recommendations. Each of these sectors counts more than 1.000 suggestions, and they together provide as much as 75 percent of the total number of recommendations. Hence, the discussion of the successive analyses is limited to the following sectors:

- ISIC 25 - Manufacture of fabricated metal products, except machinery and equipment;
- ISIC 22 - Manufacture of rubber and plastics products;
- ISIC 28 - Manufacture of machinery and equipment (non-electrical);
- ISIC 24 - Manufacture of basic metals;
- ISIC 10 - Manufacture of food products;
- ISIC 13 - Manufacture of textiles;
- ISIC 17 - Manufacture of paper and paper products;
- ISIC 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials.

	NUMBER OF RECOMMENDATIONS							
ISIC	**DIS - OP**	**GEN - HARD**	**USE - OP**	**TREAT - HARD**	**DIS – HARD**	**GEN - OP**	**USE - HARD**	**TOT**
25	2003	1259	296	18	7	9	3	3595
22	1115	760	173	11	6	4	3	2072
28	1118	765	149	14	8	6	1	2061
24	986	593	160	17	6	5	5	1772
10	934	476	153	16	2	11	5	1597
13	623	380	97	6	5	0	1	1112
17	609	373	77	4	3	1	1	1068
16	638	313	80	11	2	1	4	1049
23	424	219	71	7	2	3	0	726
26	369	251	39	5	3	0	0	667
20	334	206	48	5	0	1	0	594
31	315	205	49	5	1	1	1	577
27	312	204	49	0	1	0	1	567

18	306	197	33	2	0	2	1	541
11	143	95	28	1	1	1	0	269
30	149	54	22	2	2	0	0	229
21	97	58	7	3	1	0	0	166
15	83	64	8	0	0	2	0	157
29	87	56	10	0	1	0	0	154
19	63	29	8	1	1	1	0	103
32	41	30	4	1	0	0	0	76
12	13	9	6	0	0	0	0	28
14	5	3	1	0	0	0	0	9
33	1	0	0	0	0	0	0	1

Table 19 - Number of recommendations of the clusters by sector

Let us now take a more detailed look at the numbers. Reading the upper-left portion of the table by rows, it is evident that the ranking of the clusters (as for number of recommendations) is always the same across the sectors. This result is to be added with the similar ones found for the company's size and energy intensity. Namely, the operative inefficiencies in the distribution network always largely stand over the ones in the other compressed air sub-systems. Those in the generation of the compressed air (requiring hardware investments) are in second position in any sector. Reduction or elimination of misuses of the compressed air is in third position. Figure 62 visualises the situation.

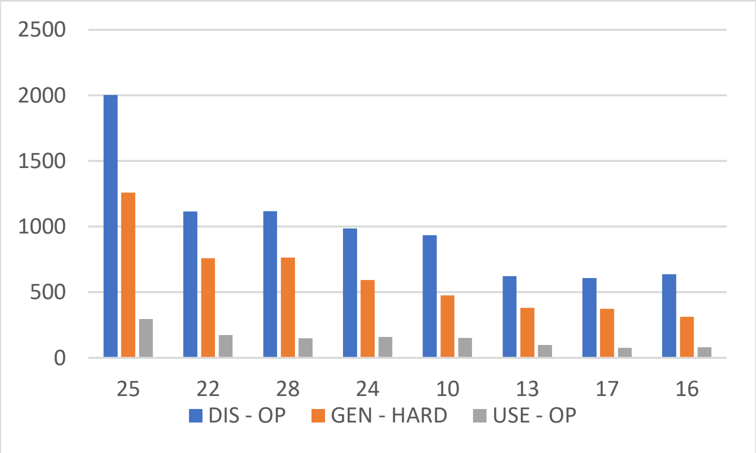

Figure 63 - Number of recommendations of the top clusters by sector

Let us move to the implementation rates, reported in Table 20 below. Before entering the details of the single clusters, it is worth considering the average values, as indicated in the last column. For this firm characteristic, some variability can be appreciated. It is certainly worth mentioning the paper sector (ISIC code 17), that stands over with a 58 percent implementation frequency. On the opposite extreme of the implementation scale figures the rubber and plastics sector (ISIC code 22), with a poor 47 percent. At this point, it seems that the sector's effect is greater than the one of company size and intensity.

	IMPLEMENTATION RATE							
ISIC	**DIS - OP**	**GEN - HARD**	**USE - OP**	**TREAT-HARD**	**DIS -HARD**	**GEN - OP**	**USE-HARD**	**AVG**
25	65%	41%	41%	33%	43%	56%	33%	56%
22	66%	36%	44%	27%	33%	25%	33%	47%
28	65%	37%	43%	57%	50%	50%	0%	50%
24	65%	43%	37%	59%	33%	40%	60%	56%
10	65%	41%	44%	69%	50%	45%	80%	56%
13	70%	36%	42%	67%	60%	N/A	100%	51%
17	65%	41%	34%	25%	0%	100%	100%	58%
16	69%	40%	39%	36%	50%	0%	25%	54%
23	67%	39%	44%	29%	0%	67%	N/A	48%
26	62%	36%	26%	40%	33%	N/A	N/A	43%
20	67%	36%	35%	20%	N/A	0%	N/A	53%
31	69%	38%	51%	40%	0%	0%	100%	45%
27	66%	43%	41%	N/A	0%	N/A	100%	53%
18	58%	38%	27%	50%	N/A	0%	0%	55%
11	61%	27%	43%	0%	0%	100%	N/A	55%
30	72%	28%	68%	100%	0%	N/A	N/A	55%
21	60%	22%	43%	0%	0%	N/A	N/A	50%
15	59%	41%	50%	N/A	N/A	50%	N/A	56%
29	76%	41%	60%	N/A	0%	N/A	N/A	53%
19	54%	31%	13%	0%	0%	0%	N/A	62%
32	76%	30%	0%	100%	N/A	N/A	N/A	61%
12	69%	44%	17%	N/A	N/A	N/A	N/A	56%
14	80%	33%	0%	N/A	N/A	N/A	N/A	54%
33	100%	N/A	N/A	N/A	N/A	N/A	N/A	100%

Table 20 - Implementation rate of the clusters by sector

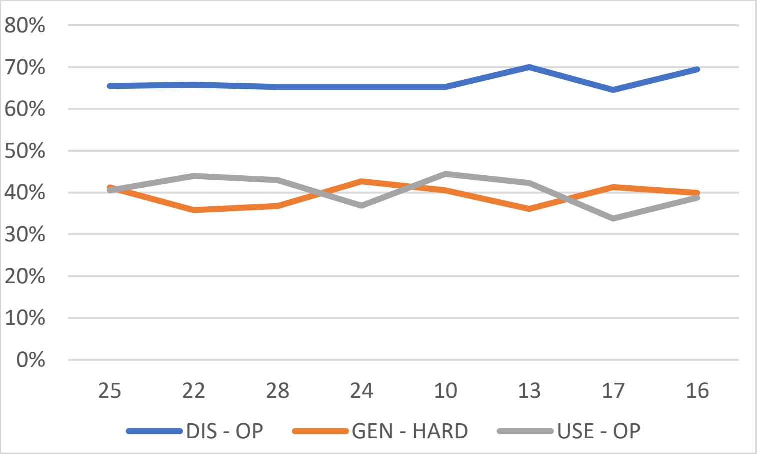

Figure 64 - Implementation rate of the top clusters by sector

Figure 64 above visualises the data in the green cells of the table. Operation and maintenance interventions in the distribution network are always the most implemented, with small variances over the industry. It may be noted the peak is in correspondence of the textile sector (ISIC code 13), equal to 70 percent. On the other hand, textile ranks last for the implementation of the interventions in the generation cluster (36 percent). In the operation-use cluster, it can be mentioned that the paper sector (ISIC code 17) (first in the general ranking) ranks last with an adoption rate of 34 percent.

4.7.2 Single interventions

The table below reports the quantity of recommendations for each intervention, and for each manufacturing branch. As it can be noted the number of recommendations rapidly drops as moving off the top left corner. For this reason, I have conservatively decided to exclude from the analysis at intervention-level the last two interventions and sectors, whose related cells are highlighted in yellow. As a result, in this paragraph I will refer only to the 30 cells corresponding to the 5 most recommended EEMs and to the 6 most assessed sectors. All but two of these cells contain more than 100 replicates, which is hopefully enough to make some solid considerations.

	NUMBER OF RECOMMENDATIONS																
ISIC	**2,4236**	**2,4231**	**2,4221**	**2,2434**	**2,4232**	**2,4226**	**2,4224**	**2,4233**	**2,4235**	**2,4222**	**2,4225**	**2,4234**	**2,4227**	**2,4237**	**2,4238**	**2,4223**	**2,2435**
25	1305	677	714	331	262	117	97	26	21	11	7	9	4	6	2	3	3
22	692	402	473	147	150	71	69	16	21	4	6	4	5	3	4	3	2
28	728	377	414	214	132	81	56	10	13	8	8	6	4	5	2	1	2
24	641	333	322	131	131	72	68	16	12	8	6	5	8	5	8	5	1
10	518	403	305	75	122	37	59	29	13	8	2	11	6	1	1	5	2
13	388	229	203	101	72	44	32	19	6	4	5	0	2	4	2	1	0
17	373	223	238	72	65	39	24	10	13	2	3	1	1	1	1	1	1
16	445	188	140	65	65	32	76	12	5	8	2	1	3	1	2	4	0
23	276	146	115	45	54	34	25	14	2	5	2	3	2	1	2	0	0
26	212	152	145	48	29	39	19	7	5	3	3	0	2	2	1	0	0
20	197	128	117	47	38	20	22	9	9	3	0	1	2	1	0	0	0
31	219	95	106	66	43	17	16	3	1	4	1	1	0	0	3	1	1
27	197	113	111	58	39	21	14	7	2	0	1	0	0	3	0	1	0

18	171	132	135	36	26	10	16	5	3	2	0	2	0	1	1	1	0
11	87	55	56	16	22	12	11	6	1	1	1	1	0	0	0	0	0
30	95	54	28	19	17	3	4	3	0	2	2	0	0	0	2	0	0
21	53	44	36	8	7	6	8	0	0	2	1	0	1	0	0	0	0
15	49	33	45	8	7	6	5	1	1	0	0	2	0	0	0	0	0
29	59	27	25	25	8	5	1	2	1	0	1	0	0	0	0	0	0
19	38	24	18	3	6	4	4	2	1	0	1	1	0	0	0	0	1
32	29	10	17	7	4	4	2	0	2	0	0	0	1	0	0	0	0
12	8	5	2	3	6	1	3	0	0	0	0	0	0	0	0	0	0
14	3	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
33	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 21 - Number of recommendations of the interventions by sector

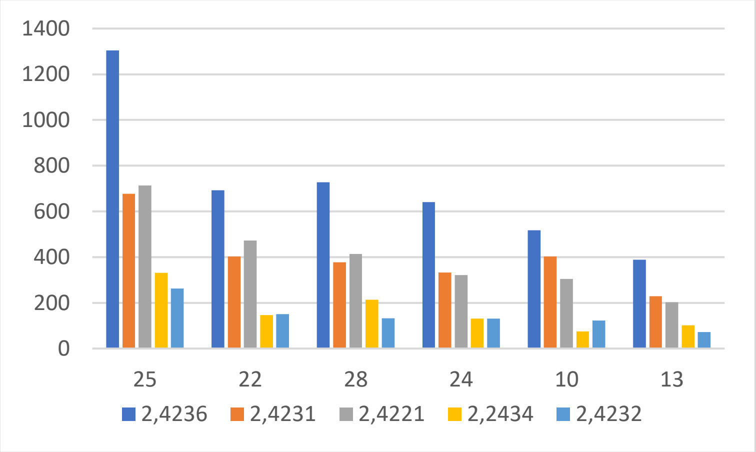

Figure 65 - Number of recommendations of the top interventions by sector

Reading the table by rows gives an indication of the ranking of the interventions in each sector, and allows to point out eventual differences with respect to the general ranking. Apart from a low number of recommendations for compressor’s heat recovery (2.2434) in the food companies (ISIC code 10), no particular differences exist. Let us instead move to the implementation rates indicated in Table 23.

	IMPLEMENTATION RATE																
ISIC	**2,4236**	**2,4231**	**2,4221**	**2,2434**	**2,4232**	**2,4226**	**2,4224**	**2,4233**	**2,4235**	**2,4222**	**2,4225**	**2,4234**	**2,4227**	**2,4237**	**2,4238**	**2,4223**	**2,2435**
25	75%	46%	41%	37%	42%	45%	54%	27%	76%	36%	43%	56%	50%	33%	0%	33%	0%

22	75%	51%	39%	23%	43%	35%	41%	44%	57%	0%	33%	25%	60%	67%	50%	33%	0%
28	76%	44%	37%	29%	45%	52%	39%	20%	77%	75%	50%	50%	50%	60%	0%	0%	0%
24	75%	47%	48%	26%	37%	43%	47%	31%	42%	63%	33%	40%	63%	40%	50%	60%	0%
10	78%	48%	46%	27%	41%	38%	34%	55%	62%	75%	50%	45%	83%	100%	100%	80%	0%
13	82%	51%	43%	23%	44%	39%	28%	32%	50%	75%	60%	N/A	50%	50%	50%	100%	N/A
17	77%	46%	43%	36%	34%	36%	46%	30%	38%	0%	0%	100%	0%	100%	0%	100%	100%
16	79%	48%	36%	40%	37%	53%	41%	42%	40%	38%	50%	0%	33%	0%	100%	25%	N/A
23	77%	47%	49%	22%	39%	32%	32%	50%	100%	40%	0%	67%	0%	100%	100%	N/A	N/A
26	75%	45%	40%	27%	28%	31%	42%	14%	20%	33%	33%	N/A	50%	0%	100%	N/A	N/A
20	80%	47%	38%	28%	37%	35%	41%	33%	67%	33%	N/A	0%	0%	0%	N/A	N/A	N/A
31	80%	43%	42%	30%	49%	29%	44%	33%	100%	50%	0%	0%	N/A	N/A	100%	100%	0%
27	77%	47%	48%	38%	38%	38%	36%	43%	50%	N/A	0%	N/A	N/A	67%	N/A	100%	N/A
18	68%	44%	42%	22%	35%	50%	31%	0%	67%	50%	N/A	0%	N/A	0%	0%	0%	N/A
11	70%	45%	29%	13%	41%	25%	45%	50%	100%	0%	0%	100%	N/A	N/A	N/A	N/A	N/A
30	79%	61%	36%	11%	76%	67%	25%	33%	N/A	100%	0%	N/A	N/A	N/A	50%	N/A	N/A
21	75%	41%	19%	38%	43%	33%	13%	N/A	N/A	0%	0%	N/A	0%	N/A	N/A	N/A	N/A
15	73%	39%	36%	50%	43%	33%	80%	100%	0%	N/A	N/A	50%	N/A	N/A	N/A	N/A	N/A
29	90%	44%	48%	36%	63%	20%	100%	50%	100%	N/A	0%	N/A	N/A	N/A	N/A	N/A	N/A
19	71%	29%	39%	33%	17%	25%	0%	0%	0%	N/A	0%	0%	N/A	N/A	N/A	N/A	0%
32	83%	60%	41%	14%	0%	25%	0%	N/A	50%	N/A	N/A	N/A	100%	N/A	N/A	N/A	N/A
12	88%	40%	50%	0%	17%	100%	67%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14	67%	100%	0%	100%	0%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
33	N/A	100%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 22 – Implementation rate of the interventions by sector

At a glance Figure 66 in the following page shows a quite relevant variability of implementation over the industrial branches. The largest difference is for the intervention 2.2434, with a 15 percent oscillation range. Its implementation is maximum in the metal products sector (ISIC 25 – 23 percent) and minimum in the plastics product (ISIC code 22 - 37 percent). It may be worth mentioning that the implementation rate of 2.4236 (Eliminate leaks in inert gas and compressed air lines/ valves) in the textile sector (ISIC code 13) is exceptionally high: 82 percent.

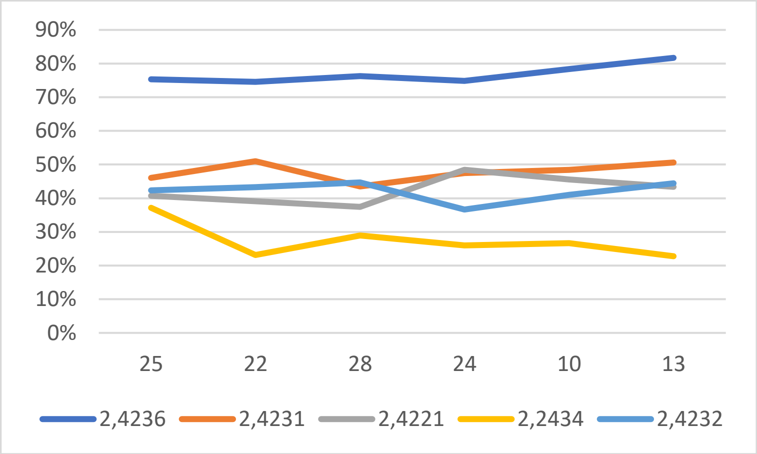

Figure 66 – Implementation rate of the top interventions by sector

In Annex B are reported the two-factor analyses which address simultaneously the effect of company size-intensity, size-sector and intensity-sector. No relevant results can be highlighted. In conclusion of this chapter, it is useful to draw some partial conclusions.

1. <u>WHERE DO ENERGY SAVINGS HIDE?</u>

- Seven out of seventeen EEMs in the compressed air cover as much as 97 percent of the total number of IAC recommendations and 95 percent of the identified energy saving potential.
- Energy-aware operation and maintenance of the distribution system is a key element to energy savings. Most of the rest of the potential can be fulfilled by machine/equipment investments in the compressor group.
- Compressed air leaks are an ever-present issue: fixing leaks represents more than one third of the total energy efficiency recommendations for compressed air.

2. <u>WHAT ABOUT THE IMPLEMENTATION OF THE INTERVENTIONS (R.O. 1)?</u>

- Overall, the implementation rate of the EEMs is low: around 1 out of 2 IAC recommendations is implemented.
- The attitude of US manufacturers towards the adoption of energy efficiency interventions for their compressed air installations has not improved over the last two decades.

2.1 IMPLEMENTATION vs CHARACTERISTICS OF THE INTERVENTION (R.O. 1)

- The operative interventions in the distribution network are the most implemented type of intervention, requiring minimal upfront cost and leading to high savings.
- On the other hand, the expansive investments in the generation group are much more often rejected.
- Fixing leaks is the intervention with highest implementation rate, resulting from a combination of exceptional cost-effectiveness and non-energy benefits.
- On the other hand, waste heat from the compressor is recovered less than one out of three times it is suggested.

2.2 IMPLEMENTATION vs CHARACTERISTICS OF THE COMPANY (R.O. 1)

- The effect of the firms’ characteristics on the implementation is disappointingly small. However, results must be taken with caution. A key for interpreting them is to consider that data originate from a context which is not “business as usual”. Several elements can seriously jeopardise the validity of the results, including (but not only): tendering rules, IAC personnel competences (undergraduate students), psychological bias induced by the free energy consultancy.

CHAPTER 5 – BARRIERS AND DRIVERS

This chapter will provide the basic theoretical background about the barriers to and the driving forces for energy efficiency. Section 5.1 will present the taxonomy of the barriers, while section 5.2 will illustrate the one of the drivers. A reduced version of such taxonomies will be a core part of the questionnaire for the empirical investigation.

5.1 Barriers to energy efficiency

The amount of literature about the barriers to energy efficiency is rich of several contributions, both theoretical and empirical, stemming from decades of academic research on the topic. One of the most recent contributions to the theory of the barriers has been provided by (Cagno et al. 2013), who have proposed an innovative taxonomy of the barriers. Building on the major contributions from the literature, the authors have identified and overcome several issues that affected the previous works, such as missing elements, overlaps, and implicit interactions.

The taxonomy classifies the barriers into two major groups: external and internal. Hence, the external barriers are assigned to the different actors, namely *market, government/politics, technology/service suppliers, designers and manufacturers, energy suppliers* and *capital suppliers.* Internal barriers, instead, are further distinguished into *economic, behavioural, organisational, competence-related,* and *awareness*. In the following the individual barriers are briefly explained.

<u>EXTERNAL (WITH RESPECT TO THE FIRM) BARRIERS</u>

External stakeholders differently involved in the energy market can directly or indirectly generate several barriers hindering companies to undertake energy efficiency interventions.

1. Market

1.1 Energy prices distortion, due to the fact that energy prices do not account for externalities, such as the different generation cost during the day;

1.2 Low diffusion of technologies, which is typical of innovative technologies;

1.3 Low diffusion of information, as it takes time to refine and disseminate information on energy efficient technologies;

1.4 Market risks, such as uncertainties about energy prices;

1.5 Difficulty in gathering external skills, namely low availability and/or high cost of experts.

2 Government/politics

2.1 Lack of proper regulation reflects a lack of standards or classes for energy performance;

2.2 Distortion in fiscal policies, such as taxes, subsidies, or other policy interventions that discourage the adoption of energy efficient technologies.

3 Technology/services suppliers

3.1 Lack of interest in energy efficiency, as they may get higher returns in commercializing lower energy efficient technologies;

3.2 Technology/services suppliers not up to date, causing their customers to be not adequately informed;

*3.3 Scarce communication skill*s, which may cause energy-efficient technologies to be ignored by customers.

4 Designers and manufacturers

4.1 Technical characteristics not adequate, due to the fact that energy-efficient technologies might be very particular;

4.2 High initial costs, that can be considered a barrier not only to customers, yet also to designers and manufacturers of technologies.

5 Energy suppliers

5.1 Scarce communication skills, such as options in energy contracts presented in an unclear way;

5.2 Energy prices distortion, for example decreasing unit cost as consumption increases*;*

5.3 Lack of interest in energy efficiency, because customers' energy costs reduction implies lower returns for energy suppliers.

6 Capital suppliers

6.1 Costs to investigate debt carrying capability, namely the high transaction costs to evaluate debt carrying capability of potential clients;

6.2 Difficulty to identify the quality of investments, which might cause capital providers to grant money only to well-known solutions.

INTERNAL (WITH RESPECT TO THE FIRM) BARRIERS

Several barriers are originated within the firm itself, independently of the external actors.

7 Economic

Economic barriers are related to the economic evaluation of an energy efficiency investment.

7.1 Low capital availability, the firm does not have sufficient own capital to invest in energy-efficient technologies;

7.2 Hidden costs, which can be incurred before the intervention, during the implementation of the investment, and after the intervention;

7.3 Intervention-related risks, namely uncertainties and risks that may occur when implementing the energy efficiency interventions;

7.4 Interventions not sufficiently profitable, some enterprises often rationally discard investments with a rate of return lower than their internal rate of return.

8 Organizational

Organizational barriers are generated by the interaction of different functions within a company.

8.1 Low status of energy efficiency, namely the functions devoted to energy management do not have sufficient power to act effectively to improve energy efficiency;

8.2 Split incentives, the decision-maker might not gain the benefits from improving energy efficiency;

8.3 Complex decision chain, if the decision-making process involves several functions, the information flow might not be straight and smooth.;

8.4 Lack of time, the decision- maker does not have enough time to consider energy efficiency opportunities*;* and

8.5 Lack of internal control, without an adequate control system established by the management the personnel may not implement energy efficiency practices.

9 Behavioural

Behavioural barriers are related to the behaviour of operators and decision-makers within the firm.

9.1 Lack of interest in energy efficiency, due to the small weight of energy cost with respect to the firm's production cost and/or because the firm perceives itself as already efficient;

9.2 Other priorities, which seems particularly critical for SMEs, where decision-makers might be focused almost uniquely on few core business activities;

9.3 Inertia, namely the resistance to change and risk;

9.4 Imperfect evaluation criteria, the decision-makers might lack the proper knowledge or criteria to evaluate investments;

9.5 Lack of sharing the objectives, namely misalignments between the behaviour of personnel and energy management objectives.

10 Competences

Specific in-house competences are necessary to implement energy efficiency interventions.

10.1 Identifying the inefficiencies indicates a lack of competences on methods and tools to identify energy waste;

10.2 Identifying the opportunities represents the difficulty to identify the opportunities to improve energy efficiency;

10.3 Implementing the interventions, shows the difficulty to implement practices and interventions for energy efficiency.

11 Awareness

11.1 Lack of awareness (or *ignorance*), refers to the fact that decision makers simply ignore the possible benefits coming from the implementation of energy efficiency opportunities.

The barriers' taxonomy is summarized in the table in the next page.

ORIGIN	ACTOR/AREA	BARRIER
EXTERNAL	Market	Energy prices distortion
		Low diffusion of technologies
		Low diffusion of information
		Market risks
		Difficulty in Gathering External Skills
	Government/politics	Lack of proper regulation
		Distortion in fiscal policies
	Technology/services suppliers	Lack of interest in energy efficiency
		Technology suppliers not updated
		Scarce communication skills
	Designers and manufacturers	Technical characteristics not adequate
		High initial costs
	Energy suppliers	Scarce communication skills
		Distortion in energy policies
		Lack of interest in energy efficiency
	Capital suppliers	Costs to investigate debt carrying capability
		Difficulty in identifying the quality of the investments
INTERNAL	Economic	Low capital availability
		Hidden costs
		Intervention-related risks
		Interventions not sufficiently profitable
	Organisational	Low status of energy efficiency
		Divergent interests
		Complex decision chain
		Lack of time
		Lack of internal control
	Behavioural	Lack of interest in energy efficiency
		Other priorities
		Inertia
		Imperfect evaluation criteria
		Lack of sharing the objectives
	Competences	Identifying the inefficiencies
		Identifying the opportunities
		Implementing the interventions
	Awareness	Lack of awareness or ignorance

Table 23 - Theoretical taxonomy of the barriers to energy efficiency (Cagno et al. 2013)

Starting from this taxonomy (Cagno et al. 2013) also developed another taxonomy, more suitable for the empirical investigation. To do so, the authors analysed the effect of the external barriers on the firm, i.e. how external impact on the energy users. Hence, they made two major changes:

1. they added some barriers to the existing clusters of internal barriers: *investment costs* and *external risks* to the economic group, and *difficulty in gathering external skill*s within competence-related barriers; and
2. they added two further clusters of barriers, namely *technology-related barriers* and *information barriers.* The former includes *technologies not adequate* (which reflects the *barrier technical characteristics not adequate*) and *technologies not available (*which reflects both *low diffusion of technologies* and *lack of interest in energy efficiency* of technology providers*).* Information barriers are the effect of many external barriers on the firm, and include *lack of information on costs and benefits, unclear information by technology suppliers, trustworthiness of the information source* and *information issues on energy contracts.*

The authors also remark that the external barriers reflect on economic, information and technology-related barriers, whereas organizational and behavioural barriers are purely internal barriers, basically independent of the external context (the only exception being *lack of interest in energy efficiency*).

In regard with the scope of this thesis, a reduced version of the empirical taxonomy has been included in the questionnaire. This is made up of the seven outer clusters of barriers. For the sake of clarity, some specific barriers have been included in the questionnaire to provide the respondents some practical examples of the meaning of the investigated macro-barriers. The table below summarises the empirical taxonomy used in the survey. Its Italian version can be found in Annex B together with the other sections of the questionnaire.

INVESTIGATED BARRIER	**SPECIFIC BARRIER**
1 TECHNOLOGY	TECHNOLOGY NOT ADEQUATE
	TECHNOLOGY NOT AVAILABLE
2 INFORMATION	LACK OF INFORMATION ON COSTS AND BENEFITS
	UNCLEAR INFORMATION BY TECHNLOGY PROVIDERS
	TRUSTWORTHINESS OF THE INFORMATION SOURCE
	INFORMATION ISSUES ON ENERGY CONTRACTS

3 ECONOMIC	LOW CAPITAL AVAILABILITY
	INVESTMENT COSTS
	HIDDEN COSTS
	INTERVEVENTION-RELATED RISKS
	EXTERNAL RISKS
	INTERVENTIONS NOT SUFFICIELNTLY PROFITABLE
4 ORGANISATIONAL	LOW STATUS OF ENERGY EFFICIENCY
	DIVERGENT INTERESTS
	COMPLEX DECISION CHAIN
	LACK OF TIME
	LACK OF INTERNAL CONTROL
5 BEHAVIORAL	LACK OF INTEREST IN ENERGY-EFFICIENCY INTERVENTIONS
	OTHER PRIORITIES
	INERTIA
	IMPERFECT EVALUATION CRITERIA
	LACK OF SHARING THE OBJECTIVES
6 COMPETENCES	IDENTIFYING THE INEFFICIENCIES
	IDENTIFYING THE OPPORTUNITIES
	IMPLEMENTING INTERVENTIONS
	DIFFICULTY IN GATHERING EXTERNAL COMPETENCIES
7 AWARENESS	LACK OF AWARENESS OR IGNORANCE

Table 24 – Taxonomy of the barriers to energy efficiency used in the empirical investigation (Cagno et al. 2013)

5.2 Driving forces for energy efficiency

The literature on the driving forces for energy efficiency is significantly lower than the one the barriers, both in terms of empirical investigations and theoretical models. In effect, the discussion about the driver has been largely neglected in the past, and has only recently started to be recognised as a key factor for the full understanding of the energy efficiency gap.

In this sense it must be reminded a very recent contribution provided by (Trianni, Cagno, Marchesani, et al. 2016), who designed novel taxonomy of the drivers for energy efficiency. Starting from a thorough literature review on the studies dealing with definition and empirical research about drivers, the authors eventually identified twenty-three independent drivers classified according to eight clusters, such as *regulatory internal, regulatory external, economic internal, economic external, informative internal, informative external, vocational training internal, and vocational training external.* In addition, the authors made the effort to identify the major stakeholders that can foster the external drivers. A simplified version of the original work which does not include the role of the stakeholders will be presented here next, as it will constitute the fifth and final part of the questionnaire used in the investigation among Italian companies.

1 Regulatory internal

1.1 Green image: green brand has been recognised as an effective marketing strategy, with more and more clients becoming increasingly willing to pay a premium for environmental friendly products.

1.2 Long-term energy strategy: long term energy strategy is a basic feature of any successful energy and environmental management systems.

1.3 Voluntary agreements: they are agreements of a company with a governmental entity or with another private company. It has been one of the most effective tools for promoting energy efficiency in several countries.

1.4 Willingness to compete: energy efficiency is not just about cost reduction. Instead, several studies explain that it can be a source of competitive advantage to achieve business targets.

2 Regulatory external

2.1 Clarity of information: unclear information such as lack of standards inhibits energy efficiency.

2.2 Efficiency due to legal restrictions: in the “stick and carrot” policy framework, this driver is exactly the stick. It refers to obligations that force companies to improve their energy savings, penalties being various forms of fines.

2.3 External energy audit/sub metering: an energy audit allows to measure and map the consumption of energy at the plant. There are various forms of audits that external companies, such as ESCOs, can offer to companies at different price. In any case an energy audit is the first step for becoming energy efficient, as you cannot improve what you cannot measure.

2.4 Increasing energy tariffs: as the energy prices increase, the share of energy cost on the total production costs increases as well. This draw the attention of plant engineers and managers to energy efficiency as a way to lower costs.

2.5 Technological appeal: like home items and clothes, also industrial equipment is more attractive when it looks modern, appealing and fashionable.

2.6 Trustworthiness of information: when the information is provided by a source which is considered unreliable, then also good information may be disregarded. This driver refers to the problem of credibility and trust.

3 Economic internal

3.1 Cost reduction from lower energy use: the lower the energy use, the lower the energy cost. This provides a good motivation to business whose ultimate purpose is survive and make profit.

3.2 Information about real energy cost: the energy price seen by the users is not the real price, as it typically does not take into account for all externalities. Information of the full price would let the market to move towards a more efficient status without the need of governmental actions.

4 Economic external

4.1 Management support: larger energy efficiency projects are often quite complex, involving competences from the design to the implementation phase. Sometimes managers lack such capabilities thus renouncing to energy efficiency possibilities. External stakeholders such as ESCOs can play an important role in this sense.

4.2 Public investment subsidies: monetary benefits from the implementation of an energy efficiency intervention is seen as an appealing chance by companies.

4.3 Private financing: monetary support such as loans is often crucial to allow companies which lack of liquidity to undertake projects. Third-party financing is a form of private financing that is quite popular with the ESCO business model.

5 Informative internal

5.1 Knowledge of non-energy benefits: besides direct energy savings, energy efficiency leads to several other indirect benefits, such as improved indoor environment, comfort, health, quality, safety, productivity, reduced noise, labour and time savings.

5.2 Management with ambitions: a management with ambitions in regards with energy efficiency can targets his/her power to foster energy efficiency within the organization.

5.3 Staff with real ambitions: this is a crucial element to actually achieve energy efficiency results. If workers are not committed to the energy cause, savings are difficult to achieve.

6 Informative external

6.1 Availability of information: a reasonable amount of good information is the first requirement of industrial decision makers to make well-informed decisions. Thus, policy makers should realise appropriate conditions and incentives for market stakeholders.

6.2 Awareness: if there is no awareness about the energy efficiency issues, it is probably difficult to achieve effective savings, simply because people either do not implement energy efficiency measures, or implement them without knowing why.

6.3 External cooperation: collaboration with other companies in the business cluster (e.g. suppliers, clients, and competitors) can allow companies to remain well-informed.

7 Vocational training internal

7.1 Programs of education and training: being able of correctly manage, operate and maintain a new energy efficient technology is as important as its energy efficiency label.

8 Vocational training external

8.1 Technical support: it may be a crucial driver to overcome technical risks related to the implementation of some large energy efficiency projects, or wherever there is a lack of in-house technical competences. Several stakeholders can overcome this barrier, from installers to technology suppliers and ESCOs.

As for the barriers, also the for the drivers this thesis will investigate their effect only at cluster level. The table below reports the twenty-tree drivers in their eight clusters. The Italian version of the table used for the empirical investigation is provided in Annex B.

INVESTIGATED DRIVER	EXPLANATION
1 REGULATORY INTERNAL	GREEN IMAGE
	LONG-TERM ENERGY STRATEGY
	VOLUNTARY AGREEMENTS
	WILLINGNESS TO COMPETE
2 REGULATORY EXTERNAL	CLARITY OF INFORMATION

	EFFICIENCY DUE TO LEGAL RESTRICTIONS
	EXTERNAL ENERGY AUDIT/SUBMETERING
	INCREASING ENERGY TARIFFS
	TECHNOLOGICAL APPEAL
	TRSUSTWORTHINESS OF INFORMATION
3 ECONOMIC INTERNAL	COST REDUCTION FROM LOWER ENERGY USE
	INFORMATION ABOUT REAL COSTS
4 ECONOMIC EXTERNAL	MANAGEMENT SUPPORT
	PUBLIC INVESTMENT SUBSIDIES
	PRIVATE FINANCING
5 INFORMATIVE INTERNAL	KNOWLEDGE OF NON-ENERGY BENEFITS
	MANAGEMENT WITH AMBITIONS
	STAFF WITH REAL AMBITIONS
6 INFORMATIVE EXTERNAL	AVAILABILITY OF INFORMATION
	AWARENESS
	EXTERNAL COOPERATION
7 VOCATIONAL TRAINING INTERNAL	PROGRAMS OF EDUCATION AND TRAINING
8 VOCATIONAL TRAINING EXTERNAL	TECHNICAL SUPPORT

Table 25 - Taxonomy of the drivers for energy efficiency used in the empirical investigation (Trianni, Cagno, Marchesani, et al. 2016)

CHAPTER 6 – EMPIRICAL INVESTIGATION

The present chapter is devoted to the presentation of the empirical investigation among Italian firms about the level of implementation of selected energy efficiency interventions for the compressed air, as well as the perceived importance of barriers and drivers to their adoption. The chapter is structured in two main parts: section 6.1 that will describe the research methodology followed to prepare the investigation, and section 6.2 that will illustrate and discuss the main findings stemming from descriptive analyses of the collected data.

6.1 Research method

The presentation of the research method is further organised in two sub-sections. Paragraph 6.1.1 presents the data collection method and questionnaire structure and its content, Paragraph 6.1.2 describes instead the cases' selection procedure and the sample of companies available for the analyses.

6.1.1 Data collection and questionnaire

The data have been collected through semi-structured interviews with a representative from each company. The interviewed person was typically a maintenance responsible, a technical operator, a plant or production director, or, in the smaller firms, the owner. The interviews were conducted with the support of a questionnaire, in order to standardise the sequence in which the questions were asked and minimise the impact of contextual effects (Cagno & Trianni 2014).

Such questionnaire (reported in Annex C) consists of four main sections, and it has been designed not to be too long to limit the interview's duration, yet to provide sufficient information to accomplish the research objectives. The first part consists of questions of general information on the company and on the role of the interviewed person, such as:

- Company name;
- Location;

- Number of employees;
- Sector;
- Presence of an energy manager;
- Energy audit within the last three years; and
- Role of the respondent.

The second part focuses on technological aspects related to both the production system and the compressed air installation. Such short questions allowed to better understand the industrial sector and sub-sector of the company, contextualise the uses of the compressed air in the factory, and indirectly assess the technical knowledge of the respondent. In detail:

- Product realised and production process;
- Number and type of compressors; and
- Applications of the compressed air.

The third section includes the questions on the level of implementation of the EEMs. In order to speed up the interviews I have reduced the number of interventions investigated with respect to the full set suggested by the IAC. The main ratio behind the adjustment of the original list was to consider only the interventions that have general applicability in most compressed air systems, irrespectively of the plant design, type of equipment installed and uses of the compressed air. In the table below the interventions that have been merged are highlighted with the same colour, whereas the ones removed from the questionnaire are crossed.

		INTERVENTION TYPE	
		HARDWARE	**OPERATION/MAINTENANCE**
TARGETED SUB-SYSTEM	**GENERATION**	2.4226 USE / PURCHASE OPTIMUM SIZED COMPRESSOR 2.4224 UPGRADE CONTROLS ON COMPRESSORS 2.2434 RECOVER HEAT FROM AIR COMPRESSOR 2.4221 INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS	2.4234 COOL COMPRESSOR AIR INTAKE WITH HEAT EXCHANGER
	TREATMENT	2.4227 USE COMPRESSOR AIR FILTERS 2.4222 INSTALL ADEQUATE DRYERS ON AIR LINES TO ELIMINATE BLOWDOWN ~~2.2435 RECOVER HEAT FROM COMPRESSED AIR DRYERS~~	

	DISTRIBUTION	~~2.4225 INSTALL COMMON HEADER ON COMPRESSORS~~	2.4236 ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES ~~2.4235 REMOVE OR CLOSE OFF UNNEEDED COMPRESSED AIR LINES~~ 2.4231 REDUCE THE PRESSURE OF COMPRESSED AIR TO THE MINIMUM REQUIRED
	END-USE	2.4223 INSTALL DIRECT ACTING UNITS IN PLACE OF COMPRESSED AIR PRESSURE SYSTEM IN SAFETY SYSTEM	2.4233 ELIMINATE PERMANENTLY THE USE OF COMPRESSED AIR 2.4232 ELIMINATE OR REDUCE COMPRESSED AIR USED FOR COOLING, AGITATING LIQUIDS, MOVING PRODUCT, OR DRYING 2.4237 SUBSTITUTE COMPRESSED AIR COOLING WITH WATER OR AIR COOLING 2.4238 DO NOT USE COMPRESSED AIR FOR PERSONAL COOLING

Table 26 - Adjustment of the interventions suggested by the IAC

USE COOL AIR AT THE COMPRESSOR INLET

The interventions highlighted in yellow are: 2.4221 (INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS) and 2.4234 (COOL COMPRESSOR AIR INTAKE WITH HEAT EXCHANGER). These EEMs clearly aim at the same purpose, i.e. use cool air at the compressor intake to reduce the compression work. Thus, they can be merged into a single general intervention, such as *"Use cool air at the compressor inlet".*

2.2435 RECOVER HEAT FROM COMPRESSED AIR DRYERS (excluded)

As mentioned in Chapter 3, heat recovery is possible only from some types of air dryers, such as the refrigerant ones. Even in this case, the low temperature at which the heat is available could make it difficult to find useful applications for the recovered heat. The fact that this intervention has been recommended only 13 times by the IAC since 1994 supports these considerations.

2.4225 INSTALL COMMON HEADER ON COMPRESSORS (excluded)

This intervention is applicable only in multi-compressor installations. Furthermore, its main advantage stems from the co-ordination of the compressors using multi-unit controls, which is already included in the intervention 2.4224 (UPGRADE CONTROLS ON COMPRESSORS).

2.4235 REMOVE OR CLOSE OFF UNNEEDED COMPRESSED AIR LINES (excluded)

This intervention is applicable only when there is some equipment connected at the compressed air system which is no more used. If this does not occur then the intervention is simply not applicable. If the whole plant does not operate (such as during night) then the compressor is simply shut off, without the need of closing valves in the distribution system.

ELIMINATE COMPRESSD AIR OR REPLACE IT WITH OTHER ENERGY VECTORS

The interventions highlighted in green are: 2.4223 (INSTALL DIRECT ACTING UNITS IN PLACE OF COMPRESSED AIR PRESSURE SYSTEM IN SAFETY SYSTEM), 2.4233 (ELIMINATE PERMANENTLY THE USE OF COMPRESSED AIR), 2.4232 (ELIMINATE OR REDUCE COMPRESSED AIR USED FOR COOLING, AGITATING LIQUIDS, MOVING PRODUCT, OR DRYING), 2.4237 (SUBSTITUTE COMPRESSED AIR COOLING WITH WATER OR AIR COOLING) and 2.4238 (DO NOT USE COMPRESSED AIR FOR PERSONAL COOLING). These EEMs aim at the same purpose, i.e. eliminate some misapplications of compressed air, or substitute them with other more appropriate energy sources. Because they are specific misuses of compressed air which do not always take place, they can be merged into a single general intervention, such as *"Eliminate compressed air or replace it with other energy vectors".*

In conclusion, the list of interventions proposed in the questionnaire is shown in Table 27. These are general enough to be applicable (to a various extent) in virtually any compressed air plant. To analyse the data, the level of implementation of each of them has been assigned a numeric value using an even Likert Scale from 1 to 4, where:

- 1 – the intervention has never been implemented (0%);
- 2 – the intervention has been scarcely implemented (33 %);
- 3 - the intervention has been fairly implemented (66%); and
- 4 - the intervention has been fully implemented (100 %).

#	INTERVENTION NAME
1	USE/PURCHASE OPTIMUM SIZED COMPRESSOR
2	UPGRADE CONTROLS ON COMPRESSORS
3	RECOVER HEAT FROM AIR COMPRESSOR

4	USE COOL AIR AT THE COMPRESSOR INLET
5	USE COMPRESSOR AIR FILTERS
6	INSTALL ADEQUATE DRYERS
7	ELIMINATE LEAKS IN COMPRESSED AIR LINES/ VALVES
8	REDUCE THE PRESSURE TO THE MINIMUM REQUIRED
9	ELIMINATE OR REPLACE COMPRESSED AIR

Table 27 – Energy efficiency interventions investigated

The fourth and fifth sections are dedicated respectively to the evaluation of the importance of the clusters of barriers and drivers illustrated in Chapter 5 (listed in Tables 24 and 25). Similarly to the evaluation of the interventions, the importance of each barrier and driver as perceived by the respondent is measured using a score from 1 to 4, where:

- 1 – the barrier/driver is not important;
- 2 - the barrier/driver is scarcely important;
- 3 - the barrier/driver is fairly important; and
- 4 - the barrier/driver is very important.

6.1.2 Case selection procedure and firms' sample

I have interviewed 35 manufacturing companies in Lombardy, so as to collect the data and perform the desired analyses. Due to the small sample size, the results obtained in the analyses do not have any statistical validity. Nevertheless, they may provide some insights that can be eventually further extended, as in in line with the explorative purpose of this study.

I have set up the investigation focusing on two main company characteristics:

- Size; and
- Sector.

There are two main ratios behind this choice:

1. As discussed in paragraph 4.5.1, the number of IAC recommendations associated to the small enterprises is quite low with respect to larger companies, and the number of replicates in the analysis by size was not homogeneously distributed across the levels. Furthermore, the distribution of the companies in the IAC is incoherent with the US manufacturing landscape, which is largely composed by small enterprises. For these reasons, I have decided to better investigate the effect of company size, whose importance is often highlighted in the literature.

2. Although variability was modest, company's sector revealed to be the most promising firm attribute from the analyses of the IAC database Thus, it seemed reasonable to go ahead analysing it with the on-field investigation.

Further, there is one factor investigated in the IAC analyses that I have eventually decided to exclude from the investigation, namely energy intensity. Although this is a common company characteristic often taken into account in previous research (e.g., (Backlund, Broberg, et al. 2012)), I have decided to exclude it for two reasons: on the one hand, evidence shows an extant marked dependency between the energy intensity and the sector, especially considering the branches investigated. On the other hand, there is no agreed consensus on the thresholds for defining a company as "energy intensive". Here a wide discussion can be found, with different bodies assuming different benchmark values (e.g., (US Department of Energy 2007) and (Ministero italiano dell'Economia e delle Finanze 2013)).

With respect to the size-factor, I have clustered companies into three groups based on their number of employees, such as:

- Small (S): 10-49 employees;
- Medium (M): 50-249 employees; and
- Large (L): >250 employees.

In regard with the sector, I have focused on the following three industrial branches:

- Metalworking (MET);
- Textile (TEX); and
- Chemical (CHEM).

The metalworking sector is economically strategic in the Lombardy region as it represents the major manufacturing sector in terms of employees (more than 400.000) (Eurostat 2010). The textile sector has been historically provided a strong boost to the economy of Como (the city I live in), although it has suffered in the last decade a serious recession due a scarce competitiveness in the international markets. The chemicals, instead, is an energy intensive industry where energy represents a high share of the total costs. In a survey on the electric motors' consumption, the US Department of Energy estimated that around 28 percent of the electricity consumed by the electric motors is used to generate compressed air (United States Department of Energy 2002).

The figure below displays the number of replicates (companies) in each level of the two factors. It should be noted again that the sample size is quite limited, thus the findings must be interpreted with caution. In regard with the size factor, the majority of the interviewed companies are small (60 percent) and medium-sized (23 percent), which is in line with the research objective. On the other hand, the replicates are more homogeneously distributed across the three sectors.

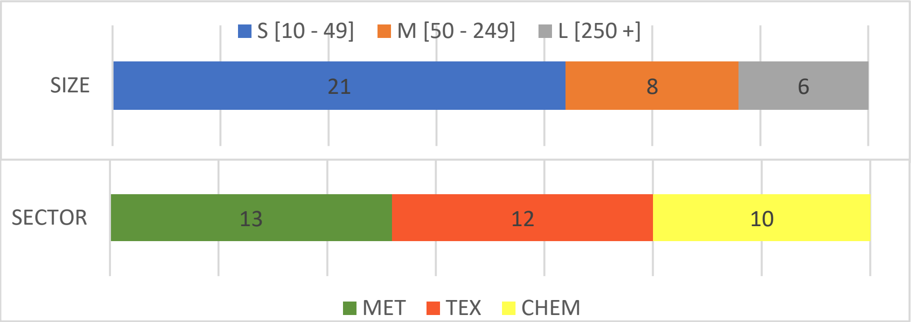

Figure 67 - Distribution of the sample by firm size and sector

6.2. Results and discussion

This section presents and discusses the main findings obtained from the data analyses of the three objects of the investigation, namely:

- Level of implementation of the interventions (6.2.1);
- Importance of the barriers hindering the adoption of the interventions (6.2.2); and
- Importance of the drivers stimulating the adoption of the interventions (6.2.3).

For each of these objects it will be first presented the average results obtained analysing the whole sample, i.e. 35 companies. Successively, it will be presented the results obtained by clustering the companies by dimension and sector. In the attempt of highlighting the major differences across the levels of such two factors, the following indicator will be used:

% DELTA (i, j) = [SCORE (i, j) – AVERAGE (i)] /AVERAGE (i)

Where SCORE (i, j) is the absolute score assigned the object investigated i (e.g. a specific barrier) in the level j of the factor investigated (e.g. SE within company size); AVERAGE (i) indicates instead the average score of the object investigated (in the example of before, the barrier). Throughout the section, I will highlight and mostly comment the greatest differences, considering as threshold values:

- 15 % (yellow) = fair difference; and
- 30 % (red) = large difference.

6.2.1 Analysis of the interventions

WHOLE SAMPLE

Figure below displays the interventions ranked from the most implemented to the least one.

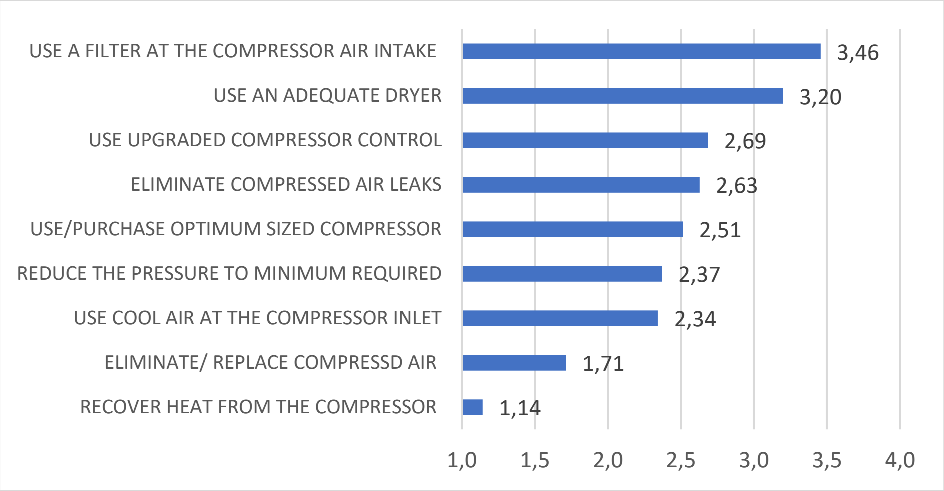

Figure 68 - Ranking of the interventions

Only two interventions overcome the implementation threshold of three. These are: *Use a filter at the compressor air intake*, which emerged as the most implemented EEM, and *Use an adequate air dryer*, which is also more than fairly adopted. Thus, from the survey, it emerged that both the compressor filter and the air dryer are components normally installed in any compressed air installation. This result is in line with the very low number of recommendations encountered in the IAC database for the corresponding interventions.

Moving to the bottom of the ranking, two EEMs resulted less than scarcely implemented (2) by the interviewed companies. These are: *Recover heat from the compressor,* which ranks abundantly last, and *Eliminate/replace compressed air,* in second-last position. About the former, a very low implementation rate (30 percent) in spite a significant number of suggestions (more than 1.500) emerged also by the analysis of the IAC database. These results suggest that such EEM face particularly high barriers that hinder its adoption. The low number of companies having eliminated or replaced compressed air (to a different extent), instead, just goes to show how difficult it is to renounce to this inefficient technology.

COMPARISON BY SIZE

Table and figure below indicate the implementation level of the interventions by companies of different size. The left side of the table highlights the most relevant differences.

	ABSOLUTE SCORE			% DELTA		
EEM	**S**	**M**	**L**	**S**	**M**	**L**
COMPRESSOR	2,19	2,88	3,17	-13%	14%	26%
CONTROL	2,38	3,13	3,17	-11%	16%	18%
HEAT RECOVERY	1,14	1,25	1,00	0%	9%	-13%
COOL INTAKE AIR	2,24	2,63	2,33	-4%	12%	0%
COMPRESSOR FILTER	3,38	3,63	3,50	-2%	5%	1%
ADEQUATE DRYER	3,24	3,00	3,33	1%	-6%	4%
ELIMINATE LEAKS	2,62	2,88	2,33	0%	9%	-11%
MIN PRESSURE	2,05	2,50	3,33	-14%	5%	41%
REPLACE CA	1,62	2,00	1,67	-6%	17%	-3%
AVERAGE	2,32	2,65	2,65	-	-	-

Table 28 - Implementation of the interventions by company size

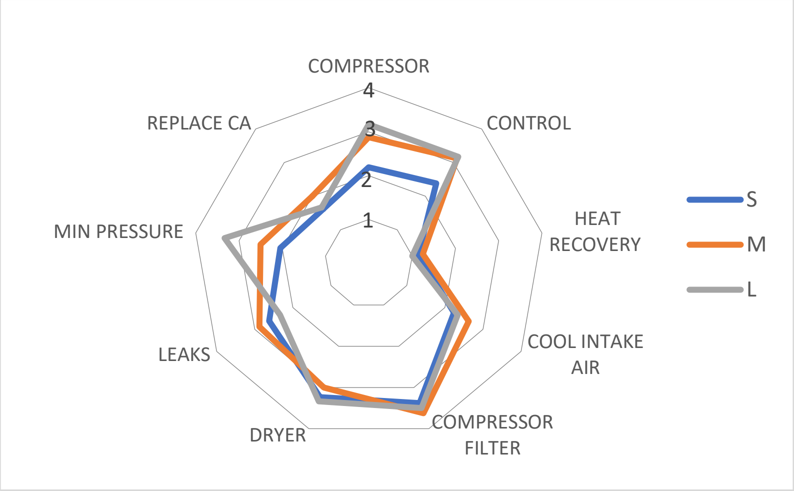

Figure 69 - Implementation of the interventions by company size

First of all, by looking at the last row of Table 28, it can be noted that the average implementation rate of SEs is lower than the one of MEs and LEs (which have an equal score). In particular, the major differences can be appreciated for three interventions, such as: *Use/purchase optimum sized compressor, Use upgraded compressor control* and *Reduce the pressure to the minimum required.* If lower adoption of the former two EEMs was somehow expected due to the high investment cost required for a new (optimally sized) compressor or for a new control, the same cannot be said for the latter intervention. In fact, the analysis of the IAC database pointed out that reducing system's pressure typically requires a minimum initial cost, in spite of the substantial energy savings it can ensures. This finding could indirectly point out the larger effect of non-economic and non-technical barriers on smaller companies. The table points out another fair difference, i.e. the higher replacement of compressed air with other technologies from medium-sized enterprises. This result is more difficult to comment and may be simply due to the limited sample investigated.

COMPARISON BY SECTOR

Table and figure below indicate the implementation level of the interventions by company sector. The left side of the table highlights the presence of two border-line differences.

	ABSOLUTE SCORE			**% DELTA**		
EEM	**MET**	**TEX**	**CHEM**	**MET**	**TEX**	**CHEM**
COMPRESSOR	2,38	2,33	2,90	-5%	-7%	15%
CONTROL	2,38	2,75	3,00	-11%	2%	12%
HEAT RECOVERY	1,23	1,17	1,00	8%	2%	-13%
COOL INTAKE AIR	2,31	2,08	2,70	-2%	-11%	15%
COMPRESSOR FILTER	3,38	3,50	3,50	-2%	1%	1%
ADEQUATE DRYER	3,23	3,17	3,20	1%	-1%	0%
ELIMINATE LEAKS	2,62	2,92	2,30	-1%	11%	-13%
MIN PRESSURE	2,23	2,42	2,50	-6%	2%	5%
REPLACE CA	1,69	1,75	1,70	-1%	2%	-1%
AVERAGE	2,38	2,45	2,53	-	-	-

Table 29 - Implementation of the interventions by company sector

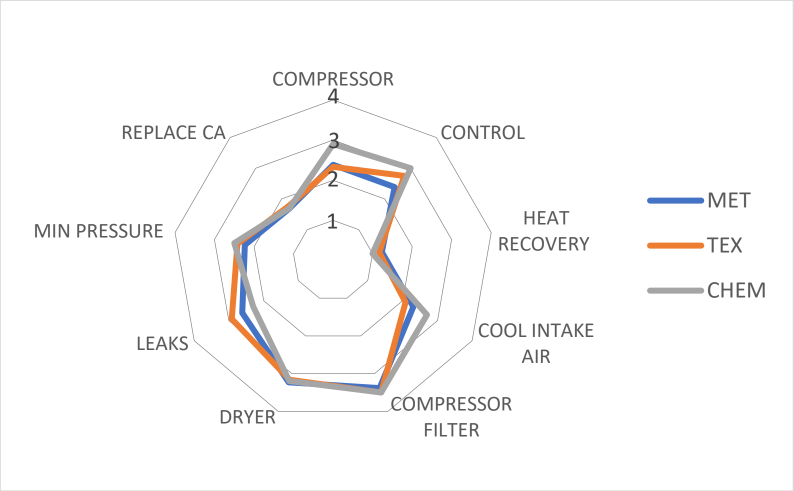

Figure 70 - Implementation of the interventions by company sector

Overall, the chemical branch shows the highest average implementation level, whereas the metalworking sector ranks last. The largest differences can be appreciated are in favour of chemical companies, which seem to be more likely to use optimally sized compressors and use cool air at the compressor intake. It may be also mentioned that in the chemical companies the elimination of compressed air leaks is less undertaken than the average (-13 percent). In effect, the larger dimension and more complex spatial layout of the chemical plants can make it difficult to regularly inspect all compressed air lines.

6.2.2 Analysis of the barriers

WHOLE SAMPLE

Figure below displays the barriers ranked from the most important to the least one.

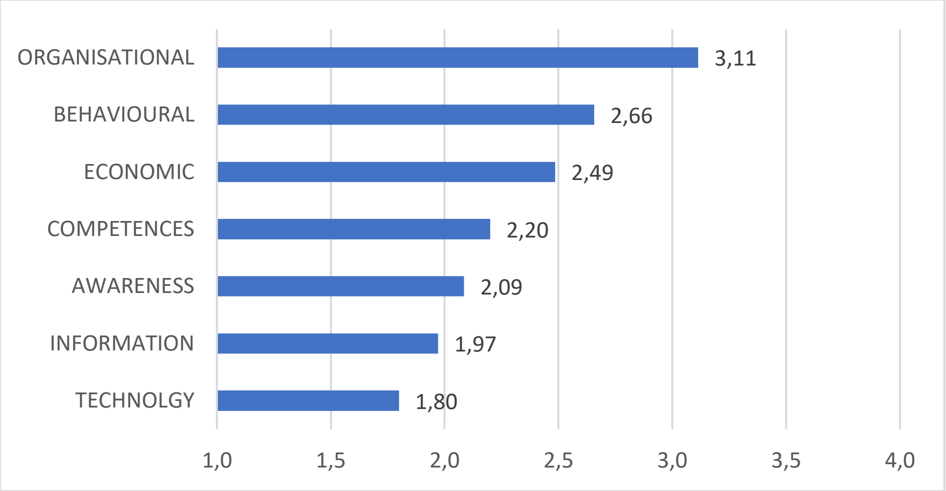

Figure 71 - Ranking of the barriers

Organisational barriers are perceived as the most important factor hindering the implementation of energy efficiency interventions in the compressed air plants. In particular, *Lack of time* to devote to the compressed air system and its energy efficiency has been very often mentioned by the respondents as a critical issue. On the other extreme of the scale in last position there are *Technology-related barriers.* Companies perceive that energy-efficient technologies are available on the market and adequate meet their needs. However, it could be mentioned an isolated case of a company complaining about the difficulty encountered for replacing some pneumatic actuators, adopted to power some presses, with more energy-efficient electric actuators. Slightly below the threshold value two, there are also *Information-related barriers*, which are perceived as scarcely important.

COMPARISON BY SIZE

Table and figure below indicate the importance of the barriers as perceived by companies of different dimension. The left side of the table suggests two fairly important differences.

	ABSOLUTE SCORE			% DELTA		
BARRIER	**S**	**M**	**L**	**S**	**M**	**L**
TECHNOLGY	1,76	1,75	2,00	-2%	-3%	11%
INFORMATION	1,90	2,13	2,00	-3%	8%	1%
ECONOMIC	2,48	2,38	2,67	0%	-4%	7%
ORGANISATIONAL	3,38	3,00	2,33	9%	-4%	-25%
BEHAVIOURAL	2,81	2,38	2,50	6%	-11%	-6%
COMPETENCES	2,33	2,13	1,83	6%	-3%	-17%
AWARENESS	2,10	2,25	1,83	0%	8%	-12%
AVERAGE	2,39	2,29	2,17	-	-	-

Table 30 - Importance of the barriers by company size

Figure 72 - Importance of the barriers by company size

Overall, SEs stated to encounter the largest problems when trying to implement the energy efficiency interventions previously discussed. The most remarkable difference can be noted in correspondence of the *Organisational barriers* (e.g. lack of time), which is by far the most critical factor perceived by the small enterprises. A similar result has been also found elsewhere in the research (e.g., (Trianni & Cagno 2012)). The major problem is that in SEs the person in charge of energy efficiency issues (usually the entrepreneur himself/herself) has also the responsibility of managing the plant, clients, suppliers, marketing etc. This fact clearly limits the time and attention that the company owner can devote to the energy efficiency issues. Another difference can be noted for *Competence-related barriers*, which are not perceived as critical by LEs and MEs. Instead, SEs admitted a lack of in-house skills to tackle energy efficiency issues, both in general and specifically for the air compressed system. As opposite to the general trend, it can be noted that SEs perceived *Information and Technology barriers* as less important than LEs, often mentioning long-lasting work relationships with trusted technology suppliers and installers. Similar result was found also by (Trianni, Cagno & Farné 2016).

COMPARISON BY SECTOR

Table and figure below indicate the importance of the barriers as perceived by companies of different sectors. The left side of the table suggests one fairly important difference.

	ABSOLUTE SCORE			**% DELTA**		
BARRIER	**MET**	**TEX**	**CHEM**	**MET**	**TEX**	**CHEM**
TECHNOLGY	1,77	1,83	1,80	-2%	2%	0%
INFORMATION	2,08	1,83	2,00	5%	-7%	1%
ECONOMIC	2,46	2,58	2,40	-1%	4%	-3%
ORGANISATIONAL	3,31	3,42	2,50	6%	10%	-20%
BEHAVIOURAL	2,77	2,75	2,40	4%	3%	-10%
COMPETENCES	2,31	2,17	2,10	5%	-2%	-5%
AWARENESS	2,08	2,25	1,90	0%	8%	-9%
AVERAGE	2,40	2,40	2,16	-	-	-

Table 31 - Importance of the barriers by company sector

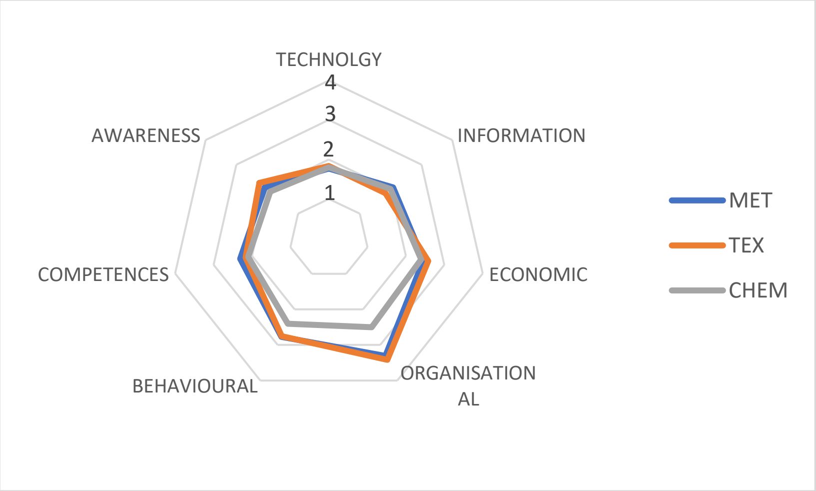

Figure 73 - Importance of the barriers by company sector

Overall, it seems that the chemical branch perceives the smallest barriers to energy efficiency. The major differences can be observed for the *Organisational barriers,* that metalworking and textile companies scored between fairly and very important (3,3 and 3,4 respectively), whereas chemical firms judged between scarcely and fairly important (2,5). This finding can reasonably reflect the higher importance and attention that chemical companies typically devote to energy issues, also considering the larger share of energy costs in the total production costs. Looking at other studies in the literature investigating barriers in different manufacturing sectors, it could be pointed out a difference from what found by (Trianni & Cagno 2012). In fact, the authors found that textile firms perceived remarkably lower barriers than companies in other sectors (such as wood, plastics, basic and primary metals). The present investigation cannot highlight the same result. A possible reason for this difference is that the present survey has investigated a much smaller sample of companies, which is almost exclusively concentrated in the city of Como.

6.2.3 Analysis of the drivers

WHOLE SAMPLE

Figure below displays the drivers ranked from the most important to the least one.

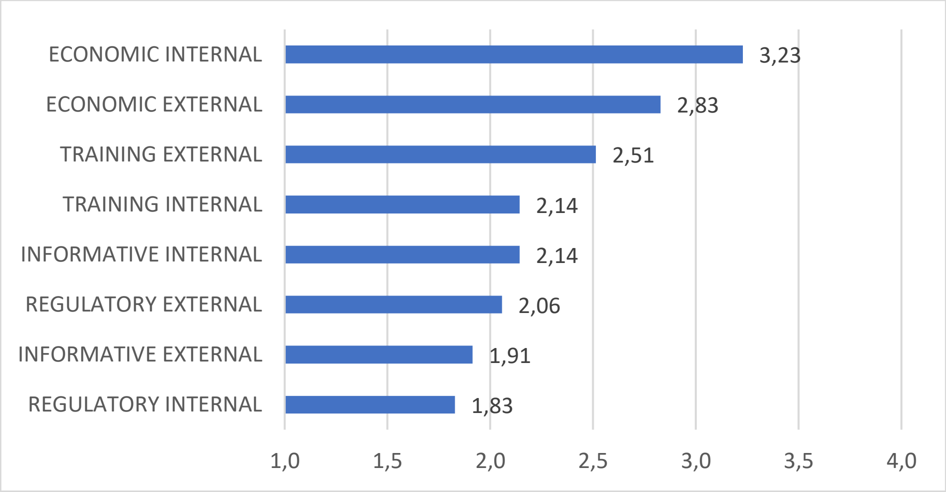

Figure 74 - Ranking of the drivers

Economic drivers are considered the most important reasons to implement the investigated energy efficiency interventions. In particular, *Economic Internal drivers* (energy cost savings) rank largely in first position and overcome the threshold value 3 (fairly important), followed by the *Economic External* ones (particularly cited *Public Investment Subsidies*) with a score of 2,8. The dominant role of economic drivers has been highlighted also in the investigation conducted by (Trianni, Cagno & Farné 2016), even though their research pointed out *Economic External drivers* to be more important than the *Economic Internal* ones. In the bottom of the ranking appear *Regulatory Internal drivers* (such as *Green Image* and *Energy Strategy*), suggesting that energy efficiency is still far from being considered an element to support the competitiveness of the firm. Below the threshold value two it can be noted also *Informative External drivers*, not particularly relevant to companies. In this regard, it can be reminded what mentioned in the previous paragraph that companies did not perceive information as a critical barrier either.

COMPARISON BY SIZE

Table and figure below indicate the importance of the drivers as perceived by companies of different dimension. In the left side of the table there are three highlighted cells, suggesting two remarkable differences and one fairly important.

	ABSOLUTE SCORE			**% DELTA**		
DRIVER	**S**	**M**	**L**	**S**	**M**	**L**
REGULATORY INTERNAL	1,76	1,75	2,17	-4%	-4%	19%
REGULATORY EXTERNAL	1,86	2,00	2,83	-10%	-3%	38%
ECONOMIC INTERNAL	3,24	3,13	3,33	0%	-3%	3%
ECONOMIC EXTERNAL	2,86	2,75	2,83	1%	-3%	0%
INFORMATIVE INTERNAL	2,05	2,38	2,17	-4%	11%	1%
INFORMATIVE EXTERNAL	1,95	1,88	1,83	2%	-2%	-4%
TRAINING INTERNAL	1,81	2,38	3,00	-16%	11%	40%
TRAINING EXTERNAL	2,71	2,25	2,17	8%	-11%	-14%
AVERAGE	2,28	2,31	2,54	-	-	-

Table 32 - Importance of the drivers by company size

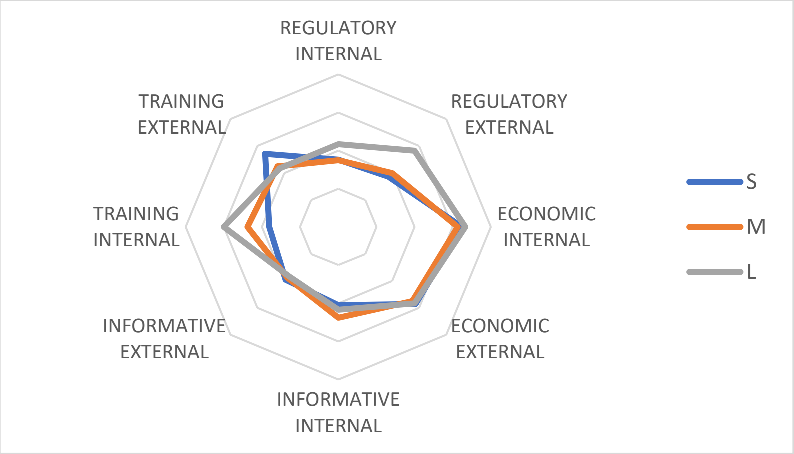

Figure 75 - Importance of the drivers by company size

In general, it seems that SEs perceive a smaller effect of the drivers to adopt energy efficiency interventions, indicating that they possibly require higher attention from policy makers to stimulate them harder. An important difference exists for *Internal Vocational Training* drivers, with large enterprises that strongly rely on internal programs of education and training, and with small companies that consider this as an irrelevant driver. Very close to the threshold value it can be noted that *External Vocational Training* drivers are largely neglected by LEs, but are considered of great support by SEs. This result is perfectly aligned with the findings presented in the barriers' section (6.2.2) which have highlighted how SEs often suffer from lack of internal competences, but do not perceive a lack of information and of technologies thanks to the support of the suppliers. Another quite interesting as well as unexpected finding is that LEs perceive *Regulatory External* drivers remarkably more important (2,8) than SEs and MEs (1,9 and 2 respectively). This result stems from the fact that large (and energy-intensive) companies are obliged by law to conduct external energy audits every 4 years (D.L. 04/07/2014, n. 102). It seems that this legal restriction has further encouraged them to improve their energy efficiency level. At the same time, LEs also perceive a stronger effect of *Regulatory Internal* drivers, such as the existence of a long-term energy strategy.

COMPARISON BY SECTOR

Table and figure below indicate the importance of the drivers as perceived by companies of different sectors. In the left side of the table there are three yellow cells, suggesting the presence of three fairly important differences.

	ABSOLUTE SCORE			**% DELTA**		
DRIVER	**MET**	**TEX**	**CHEM**	**MET**	**TEX**	**CHEM**
REGULATORY INTERNAL	1,62	1,75	2,20	-12%	-4%	20%
REGULATORY EXTERNAL	2,23	1,67	2,30	8%	-19%	12%
ECONOMIC INTERNAL	3,31	3,00	3,40	2%	-7%	5%
ECONOMIC EXTERNAL	2,62	3,17	2,70	-8%	12%	-5%
INFORMATIVE INTERNAL	2,00	1,92	2,60	-7%	-11%	21%
INFORMATIVE EXTERNAL	1,85	2,00	1,90	-4%	4%	-1%
TRAINING INTERNAL	2,15	2,00	2,30	1%	-7%	7%
TRAINING EXTERNAL	2,54	2,92	2,00	1%	16%	-20%
AVERAGE	2,29	2,30	2,43	-	-	-

Table 33 - Importance of the drivers by company sector

First of all, driving forces are overall perceived as stronger by the chemical companies than metalworking and textile ones. Remarkable exception is for *External Vocational Training* drivers, which chemical companies rate 20 percent less important than an average interviewed company. This is reasonable, considering that typically chemical companies can rely on higher in-house competences about energy and energy-related issues. The results also remark a higher weight given to *Informative Internal* drivers. This result stems from two points: on the one hand a greater knowledge of the so-called Non-Energy Benefits (NEBs), and on the other one the presence of people (management and staff) with real ambitions, which some companies recognised as a very crucial point to achieve long-lasting energy efficiency achievements. Finally, chemical companies seem to consider more important also *Regulatory Internal* drivers such as *Green Image* and *Long-term energy strategies.*

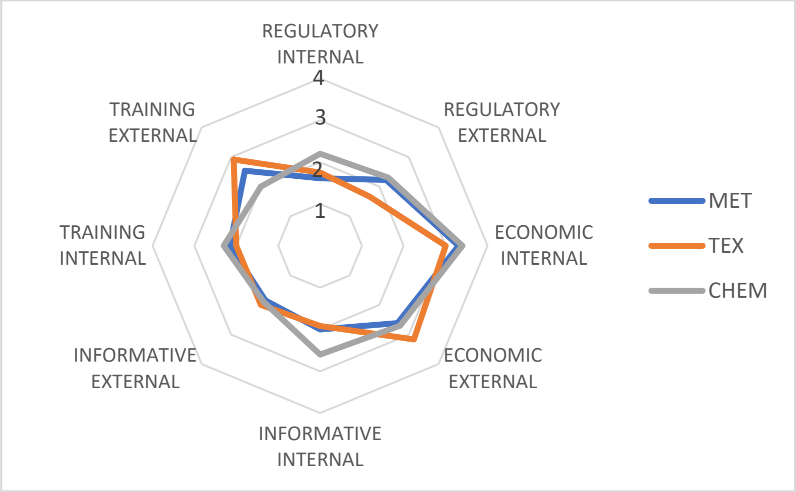

Figure 76 - Importance of the drivers by company sector

CONCLUSIONS

Modern society is called to face several challenges over the next decades, including an ever-growing energy demand, the finite nature of fossil fuels, and the global climate change due GHG emissions linked to human activities. Policy makers worldwide have recognised energy efficiency to be an effective means to tackle these issues, while securing a sustainable economic development. Nevertheless, the EU Commission has recently stated that at the current trend the energy efficiency targets set in the Climate and Energy Package will not be met, highlighting the need of further efforts from policy makers, industry and research.

The present dissertation has focused on the energy efficiency of the compressed air, an essential as much as inefficient technology used in virtually any manufacturing plant. An explorative investigation among Italian manufacturing companies has allowed gaining some insights about the level of adoption of some selected Energy Efficiency Measures (EEMs), as well as the main barriers which hinder their adoption and the main drivers that can be leveraged to overcome them. In particular, some key findings can be summarised. Firstly, results indicate that some interventions to enhance the energy efficiency of the industrial compressed air plants are scarcely implemented, such as recovering waste heat from the compressor. Despite being largely addressed in the technical and scientific literature, it seems that in the industrial practice companies largely reject its adoption. Furthermore, the study highlights that companies' attitude towards the energy efficiency of their compressed air installations is quite uneven throughout the industry. Small enterprises are the most critical, implementing interventions to a lower extent than larger companies. The gap between SEs and MEs and LEs becomes apparent when looking at the expansive hardware investments in the generation group, such as an optimum-sized compressor and an upgraded control system. In addition, SEs seem to be not fully aware of energy efficiency possibilities, as indirectly indicated by the fact that they often uselessly operate their compressed air systems at higher than needed pressure. Organisational barriers (in particular lack of time) are the considered the most critical factors hindering the implementation of energy efficiency interventions, especially by small and non-chemical companies. In addition, also competence-related barriers seem to importantly affect the SEs, which declared to often lack in-house competences to tackle energy efficiency issues, both within the compressed air area and in general. In this regard, policy makers should take action to provide SEs with an adequate technical support to both identify energy inefficiencies and implement corrective interventions. This could be achieved by fostering the already strong relationships between SEs and their technology suppliers and installers, often considered the most trusted information source. In addition, external energy audits, positively judged by large and energy intensive companies, could be extended also to the smaller companies so as to further support them with external competences. Finally, companies of any sector and size consider external economic drivers (public subsidies for energy efficiency investments) as the most important factors, second only to energy cost reductions. Taking these considerations into account, the regulatory framework should be adequately completed with economic support schemes.

The present research presents some limitations. Firstly, the small companies' sample investigated does not allow to draw any conclusion, yet only some preliminary insights. The qualitative nature of the analyses clearly reflects the explorative nature of the study. Also, several other factors besides company size and sector that have been highlighted elsewhere in the literature require to be better analysed, including the presence of an energy manager in the company and the adoption of n energy audit. Further studies should be carried out to overcome these limitations.

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Gardner Denver http://www.gardnerdenver.com/

Annex A – IAC Database structure

Assessment table

#	FIELD NAME	TYPE	DESCRIPTION
1	ID	Character	Assessment ID
2	CENTER	Character	IAC Center Code
3	FY	Number	Fiscal Year
4	SIC	Number	SIC industrial classification code
5	NAICS	Number	NAICS industrial classification code
6	STATE	Character	US State abbreviation
7	SALES	Number	Total yearly sales
8	EMPLOYEES	Number	Total site employees
9	PLANT_AREA	Number	Total plant square footage
10	PRODUCTS	Character	Types of products
11	PRODUNITS	Code	Production level units
12	PRODLEVEL	Number	Total yearly production
13	PRODHOURS	Number	Total yearly hours of operation
14	NUMARS	Number	Total number of recommendations
15	EC_plant_cost	Number	Total yearly electricity consumption costs ($)
16	EC_plant_usage	Number	Total yearly electricity consumption (kWh)
17	ED_plant_cost	Number	Total yearly electricity demand charges ($)
18	ED_plant_usage	Number	Total yearly electricity demand (kW-month-year)
19	EF_plant_cost	Number	Total yearly electricity fees
20	E2_plant_cost	Number	Total yearly natural gas consumption costs ($)
21	E2_plant_usage	Number	Total yearly natural gas consumption (MMBtu)
22	E3_plant_cost	Number	Total yearly LPG consumption costs ($)

23	E3_plant_usage	Number	Total yearly LPG consumption (MMBtu)
24	E4_plant_cost	Number	Total yearly #1 Fuel Oil consumption costs ($)
25	E4_plant_usage	Number	Total yearly #1 Fuel Oil consumption (MMBtu)
26	E5_plant_cost	Number	Total yearly #2 Fuel Oil consumption costs ($)
27	E5_plant_usage	Number	Total yearly #2 Fuel Oil consumption (MMBtu)
28	E6_plant_cost	Number	Total yearly #4 Fuel Oil consumption costs ($)
29	E6_plant_usage	Number	Total yearly #4 Fuel Oil consumption (MMBtu)
30	E7_plant_cost	Number	Total yearly #6 Fuel Oil consumption costs ($)
31	E7_plant_usage	Number	Total yearly #6 Fuel Oil consumption (MMBtu)
32	E8_plant_cost	Number	Total yearly Coal consumption costs ($)
33	E8_plant_usage	Number	Total yearly Coal consumption (MMBtu)
34	E9_plant_cost	Number	Total yearly Wood consumption costs ($)
35	E9_plant_usage	Number	Total yearly Wood consumption (MMBtu)
36	E10_plant_cost	Number	Total yearly Paper consumption costs ($)
37	E10_plant_usage	Number	Total yearly Paper consumption (MMBtu)
38	E11_plant_cost	Number	Total yearly Other Gas consumption costs ($)
39	E11_plant_usage	Number	Total yearly Other Gas consumption (MMBtu)
40	E12_plant_cost	Number	Total yearly Other Energy consumption costs ($)
41	E12_plant_usage	Number	Total yearly Other Energy consumption (MMBtu)
42	W0_plant_cost	Number	Total yearly Water consumption costs ($)
43	W0_plant_usage	Number	Total yearly Water consumption (Tgal)
44	W1_plant_cost	Number	Total yearly Water disposal costs ($)
45	W1_plant_usage	Number	Total yearly Water disposal (gal)
46	W2_plant_cost	Number	Total yearly Other Liquid (non-hazardous) disposal costs ($)
47	W2_plant_usage	Number	Total yearly Other Liquid (non-hazardous) disposal (gal)
48	W3_plant_cost	Number	Total yearly Other Liquid (hazardous) disposal costs ($)
49	W3_plant_usage	Number	Total yearly Other Liquid (hazardous) disposal (gal)
50	W4_plant_cost	Number	Total yearly Other Solid (non-hazardous) disposal costs ($)
51	W4_plant_usage	Number	Total yearly Other Solid (non-hazardous) disposal (lbs)
52	W5_plant_cost	Number	Total yearly Other Solid (hazardous) disposal costs ($)

53	W5_plant_usage	Number	Total yearly Other Solid (hazardous) disposal (lbs)
54	W6_plant_cost	Number	Total yearly Gaseous Waste disposal costs ($)
55	W6_plant_usage	Number	Total yearly Gaseous Waste disposal (lbs)

Table 34 - Data in the assessment table of the IAC database

Recommendation table

#	FIELD NAME	TYPE	DESCRIPTION
1	SUPERID	Character	Assessment ID + Recommendation Number
2	ID	Character	Assessment ID
3	AR_NUMBER	Number	Recommendation Number
4	APPCODE	Code	Application Code
5	ARC2	Code	IAC Assessment Recommendation Code
6	IMPSTATUS	Code	Implementation Status (I = implemented, N= Not Implement)
7	IMPCOST	Number	Total implementation cost
8	PSOURCCODE	Code	Primary resource identification code
9	PCONSERVED	Number	Units conserved
10	PSOURCONSV	Number	Source units conserved
11	PSAVED	Number	Cost savings
12	SSOURCCODE	Code	Secondary resource identification code
13	SCONSERVED	Number	Units conserved
14	SSOURCONSV	Number	Source units conserved
15	SSAVED	Number	Cost savings
16	TSOURCCODE	Code	Tertiary resource identification code

17	TCONSERVED	Number	Units conserved
18	TSOURCONSV	Number	Source units conserved
19	TSAVED	Number	Cost savings
20	QSOURCCODE	Code	Quaternary resource identification code
21	QCONSERVED	Number	Units conserved
22	QSOURCONSV	Number	Source units conserved
23	QSAVED	Number	Cost savings
24	REBATE	Boolean	Was a rebate involved (yes/no)
25	INCREMNTAL	Boolean	Was the recommendation implemented incrementally (yes/no)
26	FY	Number	Fiscal Year
27	IC_CAPITAL	Number	Capital component of implementation cost
28	IC_OTHER	Number	Other component of implementation cost
29	PAYBACK	Number	Simple Payback (years)
30	BPTOOL	Character	What best practice tools was used (if any)

Table 35 - Data in the recommendation table of the IAC database

Assessment Recommendation Code (ARC)

The ARC consists of a code as follows: X.YYYY.Z

- The first number, “X” is the type of recommendation. There are three types of recommendations: energy management (2), waste minimization and pollution prevention (3), direct productivity enhancements (4).

- The second four numbers, “YYYY”, detail the strategy used.
- The final number, “Z” is the application of the strategy, indicating whether the recommendation impacts the process, the building and grounds, or other application.

Energy management recommendations are those interventions aimed at eliminating the inefficient energy use. It is impossible to list here all the Energy Management Recommendations due to lack of space. Instead, the list of the clusters in which Energy Management Recommendations are grouped is provided here below. They offer a snapshot of where energy saving potential exists in a manufacturing plant.

2.Y	**2.YY**	**2.YYY**
2.1 Combustion Systems	2.11 FURNACES, OVENS & DIRECTLY FIRED OPERATIONS	2.111 Operations
		2.112 Hardware
		2.113 Maintenance
	2.12 BOILERS	2.121 Operation
		2.122 Hardware
		2.123 Maintenance
		2.124 Blowdown
	2.13 FUEL SWITCHING	2.131 Electric to Fossil Fuel
		2.132 Fossil Fuel to Electric
		2.133 Alternate Fuel
		2.139 Miscellaneous
2.2 Thermal Systems	2.21 STEAM	2.211 Traps
		2.212 Condensate
		2.213 Leaks and Insulation
		2.214 Distillation
		2.215 Maintenance
		2.216 Operations
		2.219 Miscellaneous
	2.22 HEATING	2.221 Operation
		2.222 Hardware

	2.23 HEAT TREATING	2.231 General
	2.24 HEAT RECOVERY	2.241 Flue Gas - Recuperation
		2.242 Flue Gas - Other Uses
		2.243 Heat Recovery from Specific Equipment
		2.244 Other Process Waste Heat
		2.249 Miscellaneous
	2.25 HEAT CONTAINMENT	2.251 Insulation
		2.252 Isolation
		2.253 Infiltration
	2.26 COOLING	2.261 Cooling Towers
		2.262 Chillers and Refrigeration
		2.269 Miscellaneous
	2.27 DRYING	2.271 Use of Air
2.3 Electrical Power	2.31 DEMAND MANAGEMENT	2.311 Thermal Energy Storage
		2.212 *No Longer Used*
		2.313 Scheduling
		2.319 Miscellaneous
	2.32 POWER FACTOR	2.321 General
	2.33 GENERATION OF POWER	2.331 DC
		2.332 AC
	2.34 COGENERATION	2.341 General
	2.35 TRANSMISSION	2.351 Transformers
		2.352 Conductor Size
2.4 Motor Systems	2.41 MOTORS	2.41 MOTORS
		2.413 Hardware
		2.414 Motor System Drives
		2.415 Motor Maintenance/Repair
	2.42 AIR COMPRESSORS	2.422 Hardware
		2.423 Operations

	2.43 OTHER EQUIPMENT	2.431 Operations
		2.432 Hardware
2.5 Industrial Design	2.51 SYSTEMS	2.511 Thermal
		2.512 Mechanical
		2.513 Miscellaneous
2.6 Operations	2.61 MAINTENANCE	2.612 General
	2.62 EQUIPMENT CONTROL	2.621 Equipment Use Reduction
		2.622 Equipment Scheduling
		2.623 Equipment Automation
		2.624 Load Reduction
2.7 Building and Grounds	2.71 LIGHTING	2.711 Level
		2.712 Operation
		2.713 Controls
		2.714 Hardware
	2.72 SPACE CONDITIONING	2.721 Maintenance
		2.722 Operation
		2.723 Hardware - Heating / Cooling
		2.724 Hardware - Air Circulation
		2.725 Evaporation
		2.726 Controls
		2.727 Humidity Control
		2.729 Miscellaneous
	2.73 VENTILATION	2.731 General
	2.74 BUILDING ENVELOPE	2.742 Solar Loading
		2.744 Infiltration
		2.749 Miscellaneous
2.8 Ancillary Costs	2.81 ADMINISTRATIVE	2.811 Utility Costs
		2.812 Fiscal
	2.82 SHIPPING, DISTRIBUTION, AND TRANSPORTATION	2.821 Shipping
		2.822 Vehicles

2.9 Alternative Energy Usage	2.91 GENERAL	2.911 Solar
		2.912 Wind Power
		2.913 Hydrogen

Table 36 - Clusters of the types of energy management recommendations

Resource Identification Code

STREAM TYPE	STREAM	CODE	CONSUMPTION UNITS
ENERGY	Electrical Consumption	EC	KWH(site)
	Electrical Demand	ED	MMBtu(source) kW–months/year
	Other Electrical Fees	EF	n/a
	Natural Gas	E2	MMBtu
	L.P.G	E3	MMBtu
	#1 Fuel Oil	E4	MMBtu
	#2 Fuel Oil	E5	MMBtu
	#4 Fuel Oil	E6	MMBtu
	#6 Fuel Oil	E7	MMBtu
	Coal	E8	MMBtu
	Wood	E9	MMBtu
	Paper	E10	MMBtu
	Other Gas	E11	MMBtu
	Other Energy	E12	MMBtu
WASTE REDUCTION	Water Disposal	W1	Gallons
	Other Liquid (non-haz)	W2	Gallons
	Other Liquid (haz)	W3	Gallons
	Solid Waste (non-haz)	W4	Pounds
	Solid Waste (haz)	W5	Pounds
	Gaseous Waste	W6	Pounds
RESOURCE COSTS	Personnel Changes	R1	n/a
	Administrative Costs	R2	n/a

	Primary Raw Material	R3	n/a
	Ancillary Material Cost	R4	n/a
	Water Consumption	R5	n/a
	One-time Revenue or Avoided Cost	R6	n/a
PRODUCTION	Primary Product	P1	n/a
	By-product Product ion	P2	n/a
	Increase in Production	P3	%

Table 37 - Resource identification code

Dollar value actualisation factors

YEAR	1980	1981	1982	1983	1984	1985	1986	1987
EXCHANGE RATE	4,725	3,98	3,421	2,975	2,69	2,477	2,335	2,232
YEAR	1988	1989	1990	1991	1992	1993	1994	1995
EXCHANGE RATE	2	1,995	1,88	1,767	1,676	1,609	1,548	1,469
YEAR	1996	1997	1998	1999	2000	2001	2002	2003
EXCHANGE RATE	1,414	1,39	1,365	1,344	1,31	1,276	1,246	1,216
YEAR	2004	2005	2006	2007	2008	2009	2010	2011
EXCHANGE RATE	1,192	1,172	1,149	1,13	1,095	1,087	1,07	1,042
YEAR	2012	2013	2014	2015	2016			
EXCHANGE RATE	1,011	1	0,998	0,999	1			

Table 38 - Inflation rate of the dollar

Annex B – Multifactor analyses

In order to perform the two-way analyses, I have adjusted the levels of some factors by clustering them together, to ensure a sufficient statistical soundness of the results. About the company size, I have merged small (S) with medium-size (M) enterprises, and medium-large (ML) with large (L). In so doing, two balanced levels have been obtained:

- Small-medium (SM) enterprises, with 10-99 employees (54 percent of the total recommendations); and
- Large (L) enterprises, with more than 100 employees (46 percent of recommendations).

In regard with the company sector, I have considered the five manufacturing branches with the highest number of recommendations, merging the food and the beverages sectors, and the electrical and n.e.c. machinery/equipment manufacturers. This allowed to further increase the number of replicates available. In the end, the sectors analysed are:

- 10 and 11 - Manufacture of food products and beverages (10 percent of recommendations);
- 22 - Manufacture of rubber and plastics products (11 percent);
- 24 - Manufacture of basic metals (9 percent);
- 25 - Manufacture of fabricated metal products, except machinery and equipment (19 percent);
- 27 and 28 - Manufacture of electrical and n.e.c. equipment and machinery (14 percent).

No changes have been made for the energy intensity factor. The remaining of the section is organised as follows: paragraph 4.8.1 analyses the combined effect of company size and intensity, paragraph 4.8.2 addresses company size and sector, paragraph 4.8.3 is dedicated to energy intensity and sector.

Company size and energy intensity

The table below indicates the number of recommendations and the implementation rate according to company size and energy intensity. As it can be noted the number of replicates in each level seems to be large enough to analyse the results, even though the data are unevenly distributed.

SIZE	EN INT	NUM REC	% IMP
SM	NON-INT	5040	54%
	INT	1290	56%
ML	NON-INT	4506	53%
	INT	838	55%

Table 39 - Number of recommendations and implementation rate by size and energy intensity

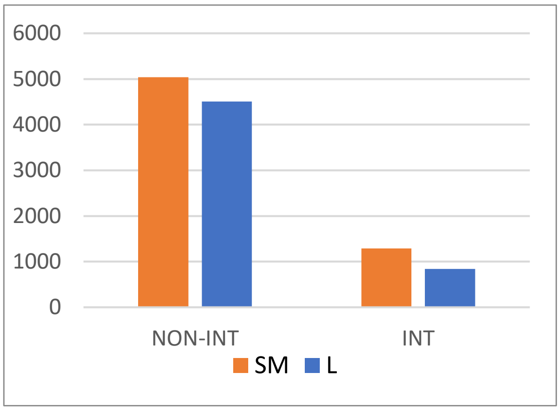

Figure 78 - Number of recommendations by size and energy intensity

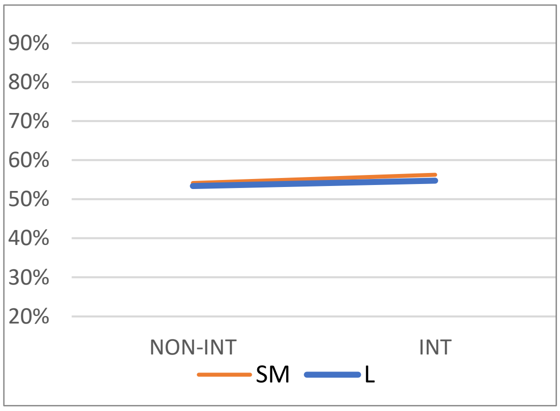

Figure 77 - Implementation rate by size and energy intensity

The interaction between company size and energy intensity factors can be visualised in Figure 68 above. As it can be noted, the lines are almost perfectly parallel, indicating that no interaction seems to exist. In effect, the differential implementation rate between non-intensive and intensive companies is equal to 2 percentage points, for both small-medium and large companies.

Company sector and size

The table below reports number of recommendations and implementation rate. Although data are dispersed on more levels (10), it seems that the number of replicates is sufficient to draw conclusions.

SECT	SIZE	NUM REC	% IMP
FOOD & BEVERAGES 10&11	SM	930	54%
	L	890	55%
RUBBER & PLASTICS 22	SM	1258	53%
	L	777	53%
BASIC METALS 24	SM	984	54%
	L	751	56%
FABRICATED METALS 25	SM	2156	56%
	L	1394	53%
	SM	1025	55%

MACHINERY & EQUIPMENT 27&28	L	1568	52%

Table 40 - Number of recommendations and implementation rate by sector and size

No large interaction effect of company size and sector seems to exist.

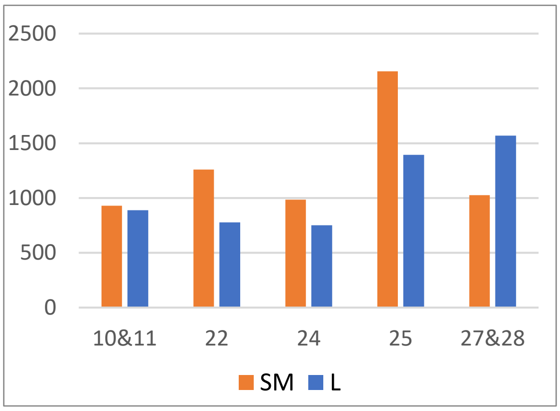

Figure 80 - Number of recommendations by sector and size

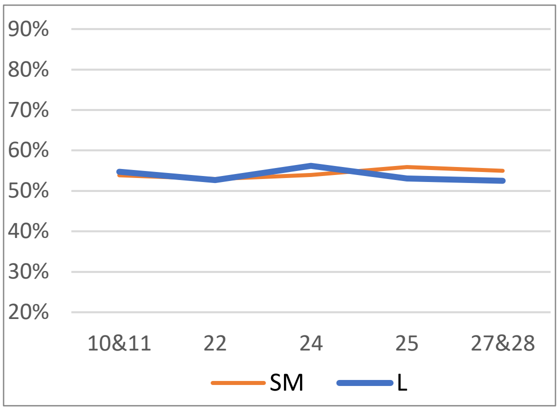

Figure 79 - Implementation rate by sector and size

Company sector and energy intensity

The table below reports the number of recommendations and implementation rate for the ten combinations of sector and energy intensity.

SECT	EN INT	NUM REC	% IMP
FOOD & BEVERAGES 10&11	NON-INT	1442	54%
	INT	374	57%
RUBBER & PLASTICS 22	NON-INT	1618	52%
	INT	422	55%
BASIC METALS 24	NON-INT	1193	54%
	INT	535	57%
FABRICATED METALS 25	NON-INT	2935	55%
	INT	606	55%
MACHINERY & EQUIPMENT 27&28	NON-INT	2384	53%
	INT	201	56%

Table 41 - Number of recommendations and implementation rate by sector and intensity

Also in this case overlapping of lines is minimal, not enugh to make any attemp of assertation.

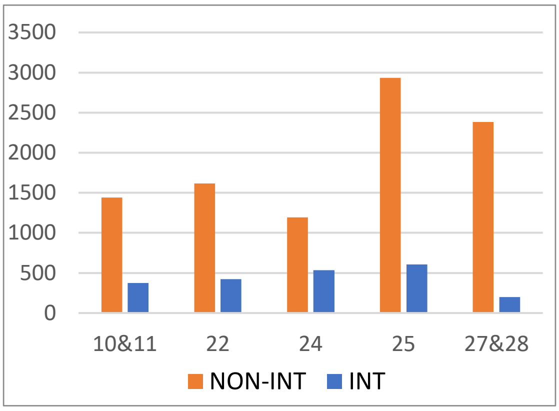

Figure 82 - Number of recommendations by sector and intensity

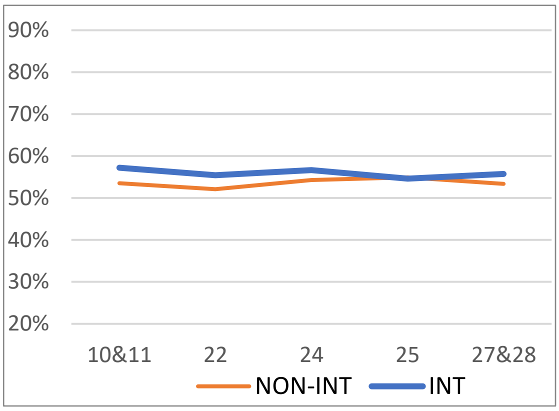

Figure 81 - Implementation rate by sector and intensity

Because of the lack of evidence of two factor interaction, and the small effect shown in the one factor analyses, it has been considered worthless to carry out a three-factor analysis.

Annex C - Questionnaire

1. INFORMAZIONI AZIENDA

1. Nome azienda: ………………………………………………………………………………………….............
2. Luogo: ……
3. Numero addetti: …………………………………………………………………………………………………
4. Settore: ……
5. Presenza di un energy manager (Sì/NO): ……………………………………………………………….
6. Energy audit negli ultimi 3 anni (SI/NO): ………………………………………………………………
7. Ruolo intervistato: ……………………………………………………………………………………………

2. INFORMAZIONI TECNOLOGICHE

1. Processo produttivo e prodotto realizzato:

……

……

………......

2. Numero, tipologia, range di potenza dei compressori:

…….

…….

3. Per cosa viene usata l'aria compressa:

…….

…….

3. INTERVENTI DI EFFICIENZA ENERGETICA NEL SISTEMA DI ARIA COMPRESSA

Indicare in una scala da 1 a 4, dove:

- 1 = non implementato,
- 2 = poco implementato,
- 3 = piuttosto implementato,
- 4 = molto implementato,

il livello di implementazione dei seguenti interventi:

INTERVENTO	VOTO
1. Compressore ottimamente dimensionato	
2. Sistema di controllo del compressore avanzato	
3. Recupero del calore dal compressore	
4. Aria fresca all’imbocco del compressore	
5. Filtro all’imbocco dell’aria del compressore	
6. Essiccatore dell’aria adeguato	
7. Eliminazione delle perdite di aria compressa	
8. Pressione dell’aria al minimo richiesto	
9. Eliminazione/sostituzione dell’aria compressa	

4. OSTACOLI AL MIGLIORAMENTO DELLE'EFFICIENZA ENERGETICA DELL'ARIA COMPRESSA

Indicare in una scala da 1 a 4 dove:

1 = non importante,
2 = scarsamente importante,
3 = piuttosto importante,
4 = molto importante,

quanto i seguenti problemi vi hanno impedito/impediscono di implementare gli interventi elencati al punto 3):

PROBLEMI	ESEMPI	VOTO
Tecnologici	• Le tecnologie non sono disponibili sul mercato o non sono adeguate	
Informazione	• Mancanza di informazioni relative a costi e vantaggi • Informazione poco chiara da parte dei fornitori • Scarsa credibilità della fonte di informazione	
Economici	• Costo di investimento troppo elevati • Rischi legati all' intervento • Interventi poco proficui	
Comportamentali	• Scarso interesse nell'efficienza energetica • Altre priorità • Resistenza al cambiamento	
Organizzativi	• Mancanza di tempo • Processo decisionale complesso • Interessi divergenti	
Competenze	• Scarse competenze tecniche interne • Difficoltà a reperire competenze esterne	
Consapevolezza	• Poca conoscenza delle tematiche di efficienza energetica	

5. MOTIVAZIONI PER IL MIGLIORAMENTO DELL'EFFICIENZA ENERGETICA DELL'ARIA COMPRESSA

Indicare in una scala da 1 a 4 dove:

1 = non importante,
2 = scarsamente importante,
3 = piuttosto importante,
4 = molto importante,

quanto i seguenti motivi vi hanno spinto/spingono/spingerebbero ad implementare gli interventi elencati al punto 3):

MOTIVAZIONI	ESEMPI	VOTO
Norme interne	• Strategia energetica a lungo termine • Green brand/marketing • Aumento della competitività	
Norme esterne	• Restrizioni legali • Aumento del costo dell'energia • Energy audit esterni	
Economiche interne	• Risparmio sui costi dell'energia	
Economiche esterne	• Finanziamenti pubblici/privati • Supporto al management	
Informazione interna	• Conoscenza dei diversi benefici • Management/Staff ambizioso	
Informazione esterna	• Disponibilità di informazione • Cooperazioni con organizzazioni esterne	
Formazione professionale interna	• Programmi di formazione professionale	
Formazione professionale esterna	• Supporto tecnico esterno	

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