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## Carbon and energy saving markets in compressed air

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**Abstract.** CO<sub>2</sub> reduction and fossil fuel saving represent two of the cornerstones of the environmental commitments of all the countries of the world. The first engagement is of a medium to long term type, and unequivocally calls for a new energetic era. The second delays in time the fossil fuel technologies to favour an energetic transition. In order to sustain the two efforts, new immaterial markets have been established in almost all the countries of the world, whose exchanges (purchases and sales) concern CO<sub>2</sub> emissions and equivalent fossil fuels that have not been emitted or burned. This paper goes deep inside two aspects not yet exploited: specific CO<sub>2</sub> emissions and equivalent fossil fuel burned, as a function of compressed air produced. Reference is made to the current compressor technology, carefully analysing CAGI's (Compressed Air Gas Institute) data and integrating it with the PNUEROP (European Association of manufacturers of compressors, vacuum pumps, pneumatic tools and allied equipment) contribution on the compressor European market. On the base of energy saving estimates that could be put in place, this article also estimates the financial value of the CO<sub>2</sub> emissions and fossil fuels avoided.

### 1. Introduction

Fossil fuel shortage and carbon increase in the atmosphere are amongst the most important current concerns of the political actions. Carbon content increase in the atmosphere calls for a new energetic economy which can only be based on renewables: it is a mean to long term problem. Fossil fuel shortage is a short to mean term problem, dominated by public and private financial and economic interests.

Fossil fuels are responsible of almost 90 % of the final energy uses and the absolute increase of the energy produced by renewables is completely nullified, in percentage terms, by the continuous increase of the energy request. Most recent data, [1,2,3] report that global primary energy consumption accelerated in 2013 despite stagnant economic growth: it increases by 2.3 %, greater than it was in 2012 (+1.8 %). In terms of CO<sub>2</sub>, the result of this fossil economy produces a significant contribution to the continuous carbon content increase into the atmosphere.

The scientific community agrees about a positive feedback between climate change and carbon cycle. The magnitude of this feedback is at the centre of the scientific debate. Reference Institution is IPCC, [4] and, based upon current understanding, the stabilization of CO<sub>2</sub> at 450 ppm will likely result in a global equilibrium warming of 1.4°C to 3.1°C, with a best guess of about 2.1°C. This would require a reduction of current annual greenhouse gas emissions by 70-80 % by 2100. In spite of this awareness, CO<sub>2</sub> concentration ranked in 2013 at an unfortunate level of 400 ppm, so an urgent intervention should be in the agenda of policy makers. CO<sub>2</sub> emissions grew by 2.3 % in 2013 with respect to 2012, reaching the absolute value of 35.3 Gt CO<sub>2</sub>/year, [3].



Concerning fuel shortage, at present, fossil fuel reserves (P1 type) have a horizon of exhaustibility of 53 years, 55 years and 113 years for the oil, gas and coal respectively, [1,3]. New production technologies and new unconventional oil and gas sources have increased the reserve levels well above conventional availability. Almost in all the countries in the world, CO<sub>2</sub> emissions, fossil fuel saving (and energy production from renewable sources) have been committed. Target short-term year is 2020 and all the countries are very aligned to the same reduction percentages, also in those countries which were in the past, far enough to a common awareness (China, India, USA, etc...).

In order to favour the reaching of the reduction goals, some environmental new markets have been established. In many countries, under a strict public regulation and control in terms of working rules and quantities to be exchanged, CO<sub>2</sub> emission and fossil fuel saving trading markets have been launched. Similarly, Carbon taxes have been established as well as financial incentives recognized when high efficiency components are chosen. As in all the “tangible” markets a specific good is traded, on the CO<sub>2</sub> and fossil fuel saving markets, CO<sub>2</sub> and fossil fuels that have not been emitted or burned are traded. Subjects which have to reach CO<sub>2</sub> emissions or fossil fuel saving targets can buy quotas sold by subjects which sell “certified quantities” of CO<sub>2</sub> not emitted or fossil fuel not burned. The experience made till now demonstrates how far these markets are from being “ideal” (price established by demand and supply balance), but, nevertheless, CO<sub>2</sub> avoided as well fossil fuels not burned today have a “price” and they represent opportunities to sale or purchase. The compressed air sector cannot neglect this opportunity.

Compressed air makes use of electrical energy; 10 % of the industrial electricity is consumed to produce compressed air, [5-11]. This figure grows up to 20 % if other, non-industrial compressor needs are considered, like those in the residential sector, transportation, and agriculture.

Moreover, the energy saving potential of the compressed air sector is great and many studies are aligned to consider that a 40-50 % of the present consumption could be saved, [5,11,13,14]. Electricity saved means CO<sub>2</sub> not emitted and fossil fuels avoided for the respective quota.

In this paper the carbon dimension of the compressed air and the related fossil fuel saving are discussed.

By a proper elaboration of CAGI’s data [12], Carbon emission by the present compressor technology has been evaluated, as a function of pressure delivered and flow rate (machine size). Thousands of data have been re-elaborated from original datasheets in order to give consistency. The analysis made use of a wider compressor specific consumption analysis, [13] and a quantitative estimation of the potential saving in existing compressors, [14].

Based on a recent study, [7], which confirmed previous knowledge in the matter, the potential energy saving has been returned in terms of CO<sub>2</sub> and fossil fuel credits which are tradable. Making reference to the European context, in which market prices are more established, a financial value of this trading has been evaluated and the need of a common synergic action of the sector is fully justified.

## **2. Compressed air electricity consumptions**

The electricity consumption in 2012 was 18312 TWh [15] whose fossil fuel share is close to 70 %: this means almost 12820 TWh are produced by burning oil, gas and coal. The main use of electricity is for industry, transport and building. When a projection for future consumption is made, electricity consumption will grow: BRIC countries in 2020 will have a dominant share (40 %) and China will become the most important electricity user (greater than USA and Europe and close to the sum of these two). Compressed air production in developed countries accounts for a mean value around 10 % of the overall electricity consumption in the industrial sector. This share is referred to the industrial needs of compressed air. Adding all the other “compression needs” i.e. the commercial and residential markets (portable tools, air pumps, pneumatic heating, ventilation, air conditioning, personal uses, etc...), the consumption grows to 20 % of the industrial electricity needs.

An important issue is to subdivide electric energy consumption of the compressed air use into different causes: a useful concept is to consider actions external to the compressors or related to them. Required flow rate and line pressure fall into the first class; compressor energy specific consumption (kWh<sub>el</sub>/m<sup>3</sup>)

into the other class. Energy consumed for compressed air (in a specific production site) is given by the flow rate delivered multiplied by the specific energy consumption of compressors. Great leakages and lack of pressure level optimization are usually found in many compressed distribution lines. The first contribution is quantified by means of a percentage of the air wasted which ranks at the unbelievable and embarrassing level of 20-40 %. In absence of this awareness, the interventions on the compressor unit side are certainly beneficial but mostly useless.

An additional significant energy saving is related to pressure delivery optimization reachable by a proper compressed air piping design and filter replacement. Reducing pressure level represents a very effective action: the consumption of a compressor depends as first approximation of the fourth square of the pressure ratio. If pressure is decreased of one bar, it is easy to verify that reducing, for instance, from 8 to 7 pressure ratio, a saving of 10 % is reached. At higher operating pressures this benefit is lower, for example decreasing line pressure from 15 to 14 bar, the beneficial effect on the compressor consumption is reduced to 4%.

Concerning the compressor technology, the potential saving on the specific energy consumption is significant, too. A useful reference could be found in [13] in which real existing machines have been compared using the CAGI's datasheets and re-elaborated [14] in order to evaluate the maximum potential saving in existing compressors and highlight the importance of machine replacement.

### 3. Carbon dimension of the compressed air

CO<sub>2</sub> emission due to electricity production is extremely variable: it depends mainly on the share of fossil fuel used and on the global efficiency of the power plants. European emission is close to 0.325 kgCO<sub>2</sub>/kWh but the spread among different countries is great. Norway has the lowest emission factor (0.01 kgCO<sub>2</sub>/kWh), ninety times lower than Greece. Switzerland, Sweden, France, Austria, Finland, Belgium, Denmark have values below the European datum, while others countries stay above (Luxemburg, Italy, Spain, Netherlands, UK, Germany, Portugal, Ireland). Important differences are still present when comparing Europe with others territorial contexts. BRICS countries have CO<sub>2</sub> emission values well above those in Europe: 2.25 times in China, 3 times in India and South Africa. This applies also to USA, which has a specific CO<sub>2</sub> emission 1.75 greater than in Europe.

Compressed air considered as a commodity is an electricity user: it has different impacts on CO<sub>2</sub> emission in different countries. So, in the countries with higher emission factors, the energy saving potential will have a greater importance. In an extensive work [13], datasheets from CAGI were elaborated in order to compare specific energy consumption of different compressors from many manufacturers. Thousands of data points have been processed in order to compare different machines whose testing conditions were not referred to exactly the same operating conditions, [14]. The result is reported in Figure 1. An extensive analysis is available in [14]: the most interesting datum is the presence in the market of significant scatter among different machines that demonstrates the use of compressors of different design generations. Air cooled compressors, operating at 8 bar (a), at 10 m<sup>3</sup>/min have a mean specific consumption equal to 6.8 kW/m<sup>3</sup>/min with a scatter equal to 1.5 kW/m<sup>3</sup>/min. At 30 m<sup>3</sup>/min, mean specific consumption decrease to 6.5 kW/m<sup>3</sup>/min with a scatter of 1 kW/m<sup>3</sup>/min. Bigger machines (>50m<sup>3</sup>/min) have a specific consumption which approaches 6.2 kW/m<sup>3</sup>/min. The wide scatter invites to seriously consider machine replacement. Recently, PNEUROP [7] explored the compressor efficiency as function of flow rate in the European market. Recalculating specific energy consumption produces scatters very close to those found from CAGI's data. From a quantitative point of view, among different machines on the market, a difference close to 20-40 % can be reached. A useful rule of thumb can be set up for the overall energy saving in compressed air use. Considering that, simple leakage interventions could account for a reduction in flow rate of about (20-40) % and pressure refining and machine replacement could account for a specific consumption reduction close to 10% and (20-40) %, when a datum is known for the overall machine consumption reduction, the overall saving can be easily estimated by doubling this value.

Figures 2a) -2d) show the specific CO<sub>2</sub> emissions evaluated making reference to the European context (screw and sliding vane rotary types) (*ccm*: carbon per cubic meter of compressed air).

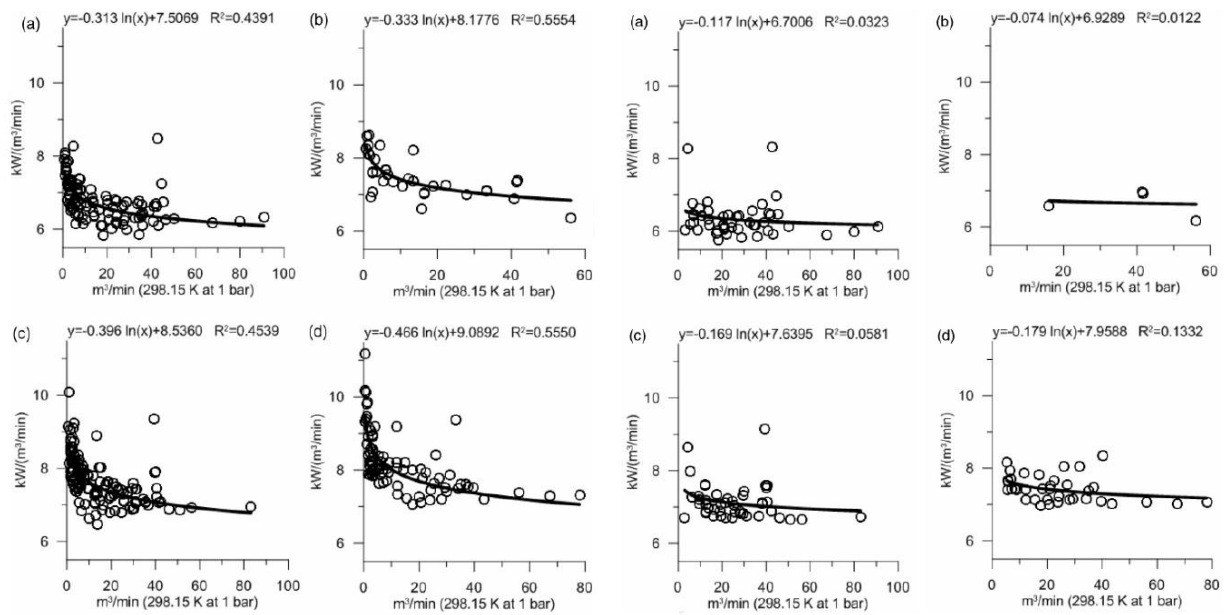


Figure 1a) Specific energy, rated flow–air cooled. Pressure delivered: (7, 8, 9, 10) bar (a)

Figure 1b) Specific energy, rated flow–water cooled. Pressure delivered: (7,8,9,10) bar (a).

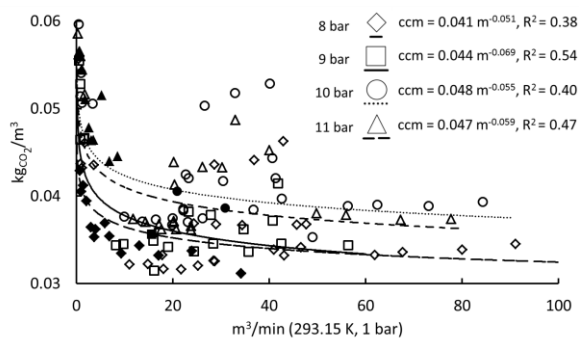


Figure 2a. Specific CO<sub>2</sub> emissions. Compressors operates at fixed speed, air cooled (black symbols refer to sliding vane rotary machines)

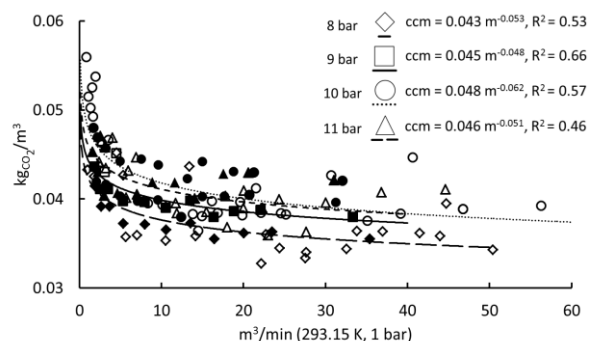


Figure 2b. Specific CO<sub>2</sub> emissions. Compressors operates at variable speed, air cooled (black symbols refer to sliding vane rotary machines).

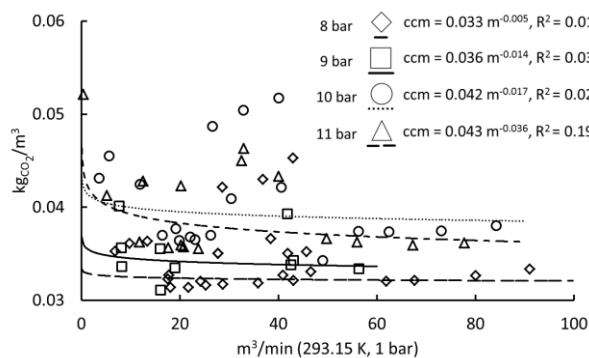


Figure 2c. Specific CO<sub>2</sub> emissions per unit mass of compressed air. Compressors operates at fixed speed, water cooled.

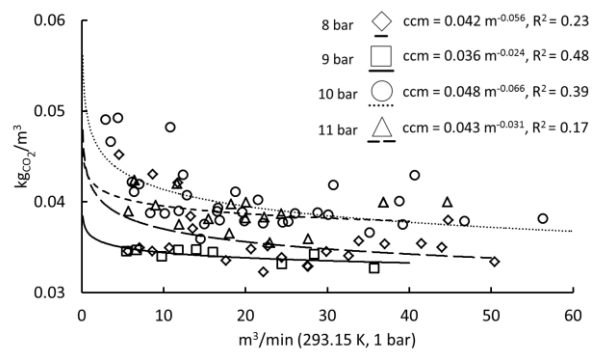


Figure 2d. Specific CO<sub>2</sub> emissions per unit mass of compressed. Compressors operates at variable speed, water cooled

The following considerations apply:

- a) *ccm* decreases in general with respect to flow rate. So, bigger machines are less polluting: for air cooled machines operating at 8 bar (a), at 5 m<sup>3</sup>/min, 20 m<sup>3</sup>/min and 50 m<sup>3</sup>/min, mean *ccm* is 0.037 kgCO<sub>2</sub>/m<sup>3</sup>, 0.035 kgCO<sub>2</sub>/m<sup>3</sup> and 0.033 kgCO<sub>2</sub>/m<sup>3</sup>, respectively. A very high scatter among machines is present, meaning the coexistence on the market of many machines conceived in the past. The scatter doesn't allow to estimate the benefit of water cooled machines (*ccm* of about 0.039 kgCO<sub>2</sub>/m<sup>3</sup>, 0.036 kgCO<sub>2</sub>/m<sup>3</sup> and 0.034 kgCO<sub>2</sub>/m<sup>3</sup> at the same flow rates);
- b) when flow rate increases, *ccm* shows an asymptotic trend, with lower values for both mean *ccm* and scatter (for a flow rate of 50 m<sup>3</sup>/min, the mean *ccm* value is about 0.033 kgCO<sub>2</sub>/m<sup>3</sup> and the scatter is 0.027 kgCO<sub>2</sub>/m<sup>3</sup>);
- c) for higher delivered pressures, *ccm* differences among air and water cooled increase, inviting to water cooled version. For a delivered pressure of 11 bar (a), the scatter further reduces, leading to a compressors population that is tightly distributed around a common value: for a flow rate of 30 m<sup>3</sup>/min, the mean *ccm* value is around 0.035 kgCO<sub>2</sub>/m<sup>3</sup>, with a scatter of about 0.002 kgCO<sub>2</sub>/m<sup>3</sup>.

## 4. Environmental related markets

### 4.1. Carbon Market

The first international attempt to reduce CO<sub>2</sub> growth in the atmosphere was introduced through the Kyoto Protocol in 1997. Reduction commitments were differentiated by country. A mean emission reduction accepted by the countries signing the Protocol was by 5% compared to 1990 level, over the period from 2008-2012. One of the ways to reach this target was the assignment of a value to Carbon not emitted.

On January 1st 2005 the European Union Emission Trading Scheme (EU-ETS) was launched. It was governed by the EU ETS Directive (2003/87/EC) and revised in 2009 (2009/29/EC). Provisions of the Directive had to be transposed into national law by 31 December 2012. The EU ETS actually covers around 11 000 large greenhouse gas emitting installations in the energy and industry sectors.

Sellers and buyers, according to defined rules, could operate on this market, so giving to sellers the possibility to make a profit and to buyers to have an additional measure to reach the emission reduction targets. The unit exchanged on this market was the ton of CO<sub>2</sub> (tCO<sub>2</sub>) avoided and it remained as unit for the others carbon-pricing instruments. Presently, EU-ETS is covers 45% of the EU's greenhouse gas emissions. On the worldwide base, EU emissions accounts for a 10-12 % of the whole emission scenario.

A "quantity-based" instrument was applied in order to define Carbon trades: policy issues a pre-determined quantity of emissions allowances and require that covered installations surrender an allowance for each ton of CO<sub>2</sub> they emit during the year. The availability of allowances (scarcity or abundance), combined with their tradability, creates a market price for allowances. This carbon price motivates committed emitters to choose between abatement options (investments) and purchasing on the market.

Carbon price on the EU-ETS market had a strong volatility, due to many aspects (political, social, related to the accountability, etc...) which have drugged the market. Today's situation is very unfortunate: 6-7 €/tCO<sub>2</sub> is the reference price due to the big oversupply of credits mainly generated by the deeply depressed economy, significant uncertainties about the allowance scarcity post-2020 and overlapping policies.

The potentiality of carbon initiatives spread all around the world: about 40 national and over 20 sub-national jurisdictions are putting a price on carbon, [16,17]. The geographical distribution of these carbon markets incorporates carbon taxes, emission trading schemes, offset and result based financing and are widespread in all the countries in the world. An important result is that the world's two largest emitters (China and USA) are also institutionalizing a carbon pricing.

Data shows carbon prices from under 0.8 €/tCO<sub>2</sub> to 150 €/tCO<sub>2</sub> and differences do not reflect the economic fundamentals of a mature market. Such a large variation of the price is related to the different measures adopted: Carbon taxes (which are fixed) or national and subnational ETS (whose price is the consequence of a traded market).

One important issue for the role of compressed air in carbon markets is the prediction of carbon price, which for sake of simplicity, here is discussed concerning EU-ETS.

The main driving factors of CO<sub>2</sub> allowance prices can be divided into two macro categories, [18]: (i) policy and regulatory issues, and (ii) market fundamentals that directly concern the production of CO<sub>2</sub> and thus demand and supply of CO<sub>2</sub> allowances. Policy and regulatory issues have a long-term impact on prices: political decisions, regulatory and operating guidelines, market events related to allowances verification, length of trading periods, uncertainty about future political decisions are among the most important causes. Market fundamentals are related to the balance between demand and supply. Demand for permits is affected by economic growth and weather; supply depends on commodity prices (coal, oil, and gas), technology advancement, renewable energy production and the importance of other existing instruments (CER, ERU, CDM, IJ). The degree of freedom accepted on allowances, banking and borrowing are additional issues which modify prices.

The copious literature on the subject is oriented to predict a price close to 12 €/tCO<sub>2</sub> at most [19], 14 €/tCO<sub>2</sub> in 2020 [20], 11.34 €/tCO<sub>2</sub> [21], 16 €/tCO<sub>2</sub> in the short term and 30 €/tCO<sub>2</sub> in the medium term [22], around 8 €/tCO<sub>2</sub> in the short term and 35 €/tCO<sub>2</sub> in the medium term [23], 15 €/tCO<sub>2</sub> in the short term and 22 €/tCO<sub>2</sub> in the medium term according to the 550 ppm scenario or 50 €/tCO<sub>2</sub> in the short term and 70 €/tCO<sub>2</sub> in the medium term according to the 450 ppm scenario [18]. Bloomberg New Energy Finance (2013) estimates a price of 30 €/tCO<sub>2</sub> without back-loading in the mean term.

For what concerns this analysis, an average value of 15 €/tCO<sub>2</sub> by 2010 has been assumed. In the eventuality of a more stringent CO<sub>2</sub> commitments, like for instance the 450 ppm scenario by IEA [3], the 30-50 €/tCO<sub>2</sub> range could be reached.

#### *4.2. Fossil fuel saving market*

As for CO<sub>2</sub>, fuel saving also is exchanged in its own market where demands of saving (requested, and therefore bought by subjects which are obliged by law to reach certain targets) is balanced by supply (offered and therefore sold, by subjects which have reached certified savings). The units exchanged are called Energy Saving Certificates (ESC) and they could be converted into equivalent fossil fuel.

ESCs have been established in several countries as a mechanism through which third parties, such as commercial and industrial companies, can help the other parties comply with the savings targets imposed on them by the local legislation. ESCs are tradable, and are associated to a unit of energy saved in electrical form or, directly, a ton of oil equivalent, TOE. This last definition allows to consider wider savings, i.e., of a thermal type.

When electrical energy saving has to be transformed into TOE, the efficiency of the electric generation must be assumed. It is quite different in different countries (30 % in France and Sweden, to 46 % in Luxembourg and Netherlands). Mean European datum is 37.5 % and, when referring it to the worldwide scenario, most part of the countries has much lower efficiency with respect to the mean averaged European level. These efficiency variations suggest a common equivalence rule in a scenario in which the ESCs markets would be homogenized and traded in all the world in order to avoid financial speculations. Same consideration applies to the carbon markets, too.

When thermal energy saving has to be transformed into TOE, the determination is much easier, being the equivalence coefficient equal to the baseline boiler or to the steam generator efficiency.

The UK was the first country to set up an Energy Savings Certificates scheme, starting in 2002. Having achieved good results during the first period (2002-2005), the mandatory savings requirement for energy suppliers was doubled, to a total of 130 TWh cumulative and actualized. The actualization takes into account the obsolescence of an energy saving device during time, from its first installation, [24].

A fossil fuel savings trading scheme has also been tested in Italy since 2005. These schemes (also implemented in Denmark and in the Flemish region of Belgium) have been recognized to be effective at the European level, as directive 2012-27-UE on energy efficiency, adopted in late 2012, requires Member States to enact similar schemes by 2014.

Many other countries have expressed an interest in this type of mechanism and are studying its applications. In USA currently, 21 states have energy efficiency targets, mandatory or voluntary; a strong diversification among them occurs, [25]. New South Wales's (Australia) ETS program is ready to be launched. Recently, India released a Climate Action Plan that encouraged the creation of a national market for ESCs and China also is debating on the scheme that should be more suitable, [26]. In general, the process of measuring the energy saved requires establishing a baseline for energy use and/or demand before and after the implementation of a project. Specific market design rules are needed in order to evaluate the effectiveness of the saving, its consistence with respect to standards, the equivalence between thermal, mechanical and electrical savings. Many compliance markets require third party verification using a measurement and verification protocol.

At the present time, the spread of these market-based tools is wide in the world. The energy saving commitments are, in fact, strongly country based, answering to specific national commitments.

One important aspect, which increases the difficulty in comparing ESCs schemes, is related to the period in which the certificates are generated and, therefore, spent.

Most established ESCs markets are certainly in Europe, in UK, France (FR), Denmark (DK) and Italy (IT): these report a main difference which is worthy of attention.

In UK, FR and DK the saving is rewarded in the year the energy saving technology takes place – all savings are calculated and contributed to the first year. The number of certificates NESCE are calculated according to the energy saving (with respect to an energy baseline consumption), to the life span (LSPAN, technical lifetime) of the activity and to a coefficient which represents the discount coefficient which considers that the original saving is diminishing during time due to the obsolescence. LSPAN is defined for different technologies and it doesn't match in different countries. These certificates are recognized the same time as the investment for the saving takes place (one at a time), supposing that the saving will take place over years thereafter.

In Italy, a financial lifespan is fixed for different energy saving actions and (5 or 8 years) and during this period certificates are paid, when the saving is in reality put in place. The value of these certificates depends on the current values on the market: so, uncertainties can occur about the future revenues. Certificates are eligible effectively when energy is saved, [27], avoiding operative risks. ESCs are expressed in TOE (Tons of oil equivalent) and a specific coefficient is introduced which transforms energy saved (thermal or electrical) into TOE. ESCs are evaluated according to a discounting procedure of the saving during the period between technological life span (LSPAN) and overall ESCs are redistributed during the overall lifespan period. A discount coefficient is defined. A comprehensive description is reported in [28, 29].

Generally speaking, price comparison among ESCs in UK, FR, DK and IT is not straightforward and advantages and drawbacks are a matter of discussion: a comprehensive analysis can be found in [30-33].

In spite of the differences, when reference is made for "conventional" saving measures (lamp, boiler replacement, insulation of building, etc...), the overall discounted financial value gets close to a common value, [24,25]. Considering the scope of the ESCs (primary energy saving in fossil fuel form), one could say that the Italian market appears to be more mature and comprehensive.

## **5. Financial value of the compressed air energy saving on the environmental markets**

Energy consumption at European level due to compressed air has been updated by PNEUROPE recently, [7]. Results of energy consumption for fixed speed compressors (screw and vanes) was 36.58 TWh, while for variable speed the figure decreases to 19.17 TWh. An overall consumption close to 56 TWh was estimated. This datum is 30 % less than a reference estimate presented in [5], equal to 80

TWh. The older estimate was produced in a period in which a weak energy saving awareness was present in the compressed air industry. Apart from the unavoidable uncertainties, the difference could be considered as the energetic improvement of the sector in the past 15 years but also as a result of the recent, still ongoing, economic crisis. Intrinsic uncertainties are very frequent when dealing with this analysis.

The potential energy saving associated to the compressor replacement in the actual European market depends on the target of the efficiency, or of the specific energy, below which a compressor can't be operated. A threshold must be defined for the compressor specific consumption dependent on flow rate and pressure delivered, or for the compressor efficiency only dependent by flow rate.

Some attempts to define an energy baseline have been done: in [34] specific energy consumption at 7 bar per Nm<sup>3</sup> (0°C@1 bar) is defined equal to 130 Wh/Nm<sup>3</sup> when premium machines are set at 85 Wh/Nm<sup>3</sup>. Nevertheless, real compressors operate at different pressures and the baseline energy datum (130 Wh/Nm<sup>3</sup>) can't be used. PNEUROP, [7], made a wider reference, introducing the adiabatic efficiency of the compressor: a wide market characterization is presented in terms of the adiabatic efficiency reported as a function of flow rate, for fixed or variable speed compressor technology. Observing the distribution of the data of different machines on the compressor adiabatic efficiency vs flow rate, some replacement scenarios have been done setting a cutoff curve for the efficiency. According to PNEUROP, an energy saving in the range 0.7-2.1 TWh is reachable for fixed speed compressors, thanks to different replacement scenarios. With the same assumptions, a saving in the range 0.3-1.2 TWh is achievable for variable speed compressors. For all compressors, 1-3.3 TWh is the potential range of achievable energy improvement.

Considering the rule of thumb, a double saving can be assumed. Therefore, 2-7 TWh can be "put on the energy saving market" if the whole compressed air chain is improved (leakages & pressure losses optimization and compressor replacement).

The quantity of CO<sub>2</sub> that could be traded is equal to 1-2.5 10<sup>6</sup> tCO<sub>2</sub>, whose value is 15-35 M€ on the ETS-EU market, at 15 €/tCO<sub>2</sub>. This result has been calculated according to the European efficiency electricity generation (0.325 kgCO<sub>2</sub>/kWh). Finally, compressed air energy saving, considering the CO<sub>2</sub> credits and ESCs, has a value in the range 165-385 M€.

In a scenario in which both energy saving and CO<sub>2</sub> reduction become more severe and stricter commitments will take place, the overall near future values could approach 200-500 M€, considering a highly plausible CO<sub>2</sub> price at 50 €/tCO<sub>2</sub>.

This result could be achieved if the compressed air sector would perform a lobby action at the European level according to which efforts done on energy efficiency by compressed air users would be recognized as tradable in the EU-ETS market.

The electrical saving of 2-7 TWh can be transformed into TOE saved, when a national average grid efficiency is defined. With an average electrical efficiency equal to 0,187 10<sup>-3</sup> TOE/kWh (Italy), the compressed air saving at European level has a value of 0.56-1.3 10<sup>6</sup> TOE. Adopting as it is allowed, a technological life span equal to 15 years and financial lifespan equal to 5 years, and an energy discounting coefficient equal to 0.02, the overall saving in the technological lifespan period is 2.65 times the saving evaluated at the first year. The overall fossil fuel saved fits in the range 1.5-3.5 10<sup>6</sup> TOE. This saving is equally redistributed in a 5 year period (financial lifespan), one-fifth of the total for each year. The corresponding financial value would be 150-350 M€ considering an average price on the market close to 100 €/TOE.

A useful number can be found referring the overall mean financial saving (assumed equal to 350 M€) to the overall electricity saving (a mean value equal to 4.5 TWh). A specific value related to the compressed air chain is equal to 8 10<sup>-2</sup> €/kWh which is really noteworthy.

A common synergic activity at the compressed air sector level should be put in place.

## 6. Conclusions

Compressed air in industry is fully based on the use of electrical energy, most part of which is produced using fossil fuels. The saving potential is huge, in a range of 25-50 % of the present consumption if leakage control, pressure readjustment, and compressor replacement are considered. This last contribution represents 50 % of the overall saving. CO<sub>2</sub> and fossil fuel savings are committed in almost all the countries in the world. Two new immaterial markets have been established: carbon and fossil fuel avoided.

Making reference to CAGI's data and to the more recent PNEUROPE analysis, the paper describes (a) the carbon dimension of the actual compressor technology, (b) the equivalent fossil fuel consumption associated to the unit of compressed air.

Concerning the carbon content of compressed air in the European context, at 8 bar (a), the CO<sub>2</sub> emission is in the range of 37-33 gCO<sub>2</sub>/m<sup>3</sup> when flow rate is in the range 5-50 m<sup>3</sup>/min respectively. This datum should be multiplied by a factor of 2.25 in China, 3 in India and South Africa and 1.75 in USA.

Specific energy consumption of different compressors reveals a significant scatter among different machines. Air cooled compressors, operating at 8 bar (a), at 10 m<sup>3</sup>/min have a mean specific consumption equal to 6.8 kW/m<sup>3</sup>/min with a scatter equal to 1.5 kW/m<sup>3</sup>/min. At 30 m<sup>3</sup>/min, mean specific consumption decreases at 6.5 kW/m<sup>3</sup>/min with a scatter of 1 kW/m<sup>3</sup>/min. Larger machines (> 50 m<sup>3</sup>/min) have a specific consumption which approaches 6.2 kW/m<sup>3</sup>/min. The scatter could be considered as the energy gain when machines are replaced.

PNEUROPE's assumptions on the energy saving referred to machine replacement in the European context is 1-3.5 TWh. An overall energy saving considering leakage control and pressure readjustment can be easily reachable. The "doubling" rule of thumb allows to estimate the overall energy saving, equal to 2-7 TWh, including a "mean" leakage control and pressure readjustment.

This result corresponds to a tradable quantity of carbon credits equal to 1-2.5 10<sup>6</sup> tCO<sub>2</sub> and to a tradable saving of fossil fuel equal to 1.5-3.5 10<sup>6</sup> TOE, considering a technological life span equal to 15 years and a financial life span equal to 5 years.

Considering a mean future carbon credit exchanged at 50 €/CO<sub>2</sub> and a mean future fossil fuel saving exchanged at 100 €/TOE, a specific market value (considering the CO<sub>2</sub> not emitted and the fuel saved) of the compressed air chain is close to 8 10<sup>-2</sup> €/kWh. This datum is close to the net electricity cost in many countries and it represents a financial potential for compressed air users which can't be neglected. A positive lobbying action of compressed air users could be done at European level.

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