Compressed air uses, efficiency, and carbon reduction: A case study

Abstract

Due to the urgency in climate change, the industry is mobilized to reduce its green gas houses. Compressed air represents nearly 10% of electricity used in industry. This case study gives a specific approach and methodology to optimize environmental and economic impact of compressed air production and uses in an industrial site. Several actions have been identified for reducing carbon emissions by 69 tons. Financial savings have also been identified on costs (up to 44 keuros) and the average payback is below 3 years.

Introduction

Compressed air is an energy widely used in the industrial sector and in service sectors. In fact, industrial compressed air is often used as a source of energy for several types of uses such as process air, pneumatic control and control of automated robots, operation of suction cups with venturi or transport of powder and granular products.

Compressed air represents nearly 10% of electricity used in industry (Widayati & Nuzahar, 2016). In order to reduce carbon footprint of the industry sector, each industrial site must reduce its compressed air consumption (Giampieri et al., 2020; Mousavi, 2014).

This paper is a case study on an industrial site. This site uses compressed air for a variety of both process and instrument air applications. It is an essential service (vital to production).

The compressed air system is currently running well but the main duty compressor is now the highest individual electricity user on site, as identified by pareto analysis of the numerous power meters that have been installed around the site.

The air system has been upgraded considerably in the past few years and in terms of compressor selection, treatment and distribution system is considered to show good practice.

The site currently has three main compressors with a very small fourth used solely at weekends to supply permanently operating equipment such as cooling towers.

The aim of this study is to identify carbon and cost savings that may be achieved.

The compressed air installation

Compressed air is generated at a central location on the industrial site to supply air at around 8 bars for process and instrumentation purposes to all areas of the site.

The air is generated by three air cooled, two stages, and oil free rotary screw compressors. One of which is fitted with variable speed drive (VSD). The two standby units are 55kW with a 160kW duty VSD which runs all week. Once production finishes on a Saturday afternoon the system is isolated and a small 2kW compressor is used solely to supply permanently operating equipment such as cooling towers. The compressors are controlled from their individual pressure switches with no central controller.

Following generation, the air is treated by filtration and desiccant dryer (to fix water molecules) to a dewpoint of -40°C by a zero-purge loss heat regenerated desiccant dryer with associated pre and after filtration. A second dryer is retained as standby but is normally isolated.

Compressed air is stored in two 2000L tanks (1 tank before dryers and 1 tank after dryers) to prevent high and variable pressure differential.

The site has a monitoring infrastructure with regards to compressed air. Power meters are installed on the main supply panel to each compressor and the main dryer, which feed back to the site Energy Monitoring System (EMS). A flowmeter, a dewpoint meter and a pressure transducer in the compressor house also feed back to the site Building Monitoring System (BMS).

The compressor house is located on the south side of the plant on an outside wall, with good ventilation on two sides.

Although the compressor room is quite compact for the amount of equipment, it is well laid out with adequate ventilation and room for maintenance. Hot exhaust air is ducted outside although there is the possibility to open it to the compressor house if the internal temperature is too cold. The hot exhaust air is also ducted to the dryer to supply the electrical regeneration air heater with hotter air than it would normally get from ambient conditions.

Compressors' performance analysis

The table 1 contains the main settings of the compressors.

Table 1: Main settings of the compressors

Compressor number	Type	Rated output (m3/hr)	Rated power (kW)	Hours run
1	Air cooled, oil free screw, VSD	1476	160	21855
2	Air cooled, oil free screw, fixed speed	468	55	14682
3	Air cooled, oil free screw, fixed speed	516	55	10901
4	Air cooled, oil free piston, fixed speed	9	2	1872
-	Total	2469	272	-

A VSD equipment present many advantages (Trianni et al., 2019). Moreover, according to Saidur et al. (2012a), using VSD systems provide the opportunity to save about 15–40% of the energy and extend equipment lifetime by allowing gentle start-up and shutdown (Saidur et al., 2012a).

The 160 kw VSD compressor (main compressor) has run to the following pattern based on data in EMS and BMS:

- Time at 0 -20% speed ➔ 0%
- Time at 20 – 40% speed ➔35%
- Time at 40 – 60% speed ➔ 36%
- Time at 60 – 80% speed ➔ 25%
- Time at 80 – 100% speed ➔ 4%

This pattern is good and indicates that the compressor has normally been operated in its efficient control range (below 80%).

Readings taken during the survey on the main compressor (160 kW) are described in the table 2.

Table 2: Readings taken during the survey

Parameter	Reading
Speed	3200 rpm
Discharge pressure	7.9 barg
Inlet filter differential pressure	0.003 bar
Oil pressure	3.6 barg
Oil temperature	44C
Interstage pressure	2.37 barg
Inlet temperature	21°C
Stage 1 exit temperature	174°C
Stage 2 inlet temperature	31°C
Stage 2 exit temperature	156°C
Compressor exit temperature	29°C

The above readings are normal, the interstage pressure is higher than expected for a fixed speed machine but fairly typical for a variable speed machine.

The compressor 2 and compressor 3 do not normally run. The compressor 2 ran for a short period after fitting a logger and showed full load power consumption of 64 kW and no load of 17.3 kW at 7.3 barg, which is in line with design figures. Both machines have low running hours and are well maintained on service contracts so we cannot expect major issues with these machines.

The small compressor is retained for weekend use and supplies few systems. This is good a practice.

Compressor control

The compressors are controlled from their individual pressure switches with no central controller. At the start of the research the settings were as follows:

- Compressor 1 = 7.9 barg
- Compressor 2 = 7.5-7.6 barg
- Compressor 3 = 6.4 – 6.9 barg

The settings on the fixed speed have been manually made to ensure the VSD stays on load. The compressor 3 setting is for emergencies only and is not considered a reasonable running pressure during production.

At high loads, the compressor 2 cycles rapidly on and off load whilst the VSD stays at maximum speed. This is due to the above settings as the VSD will only start to turn down at pressure at and above 7.9 barg whilst the compressor 1 will cycle between 7.5 and 7.6 barg.

During the research the pressures were reset as follows (immediate action):

- Compressor 1 = 7.3 barg
- Compressor 2 = 7.0-7.5 barg
- Compressor 3 =6.4 – 6.9 barg

The new settings mean that the pressure is now reduced by 0.6 barg, saving around 4% power (Kluczek & Olszewski, 2016; Grande-Acosta & Islas-Samperio, 2017), but when the demand increases above the capacity of the compressor 1 (VSD), compressor 2 will start and then go on base load as the VSD controls. Once the demand drops below the capacity of the compressor 2 and the VSD on minimum speed, the pressure will increase causing the VSD to off load and then eventually stop as the VSD takes over the load.

The average specific power consumption has been reduced from 12.66 to 12.25 kw/100Nm^3/hr. The figure of 7.3 barg was chosen as a safe level and it is likely that the pressure can be reduced further. A new set up can be put in place as long as there is no risk to production (i.e., pressure to production machines is maintained at a suitable level).

In addition to power consumption decrease at a set flow, pressure reduction also increases the maximum output from the compressor 1 (VSD). At 7 barg the maximum speed is 4300 rpm, dropping to 4020 rpm at 8.6 barg. The change from 7.9 to 7.3 barg should have increased output by around 40m^3/hr.

System demand measurement

The system demand is measured using an Endress & Hauser Mass flowmeter. The demand pattern across a typical full production week is represented in figure 1.

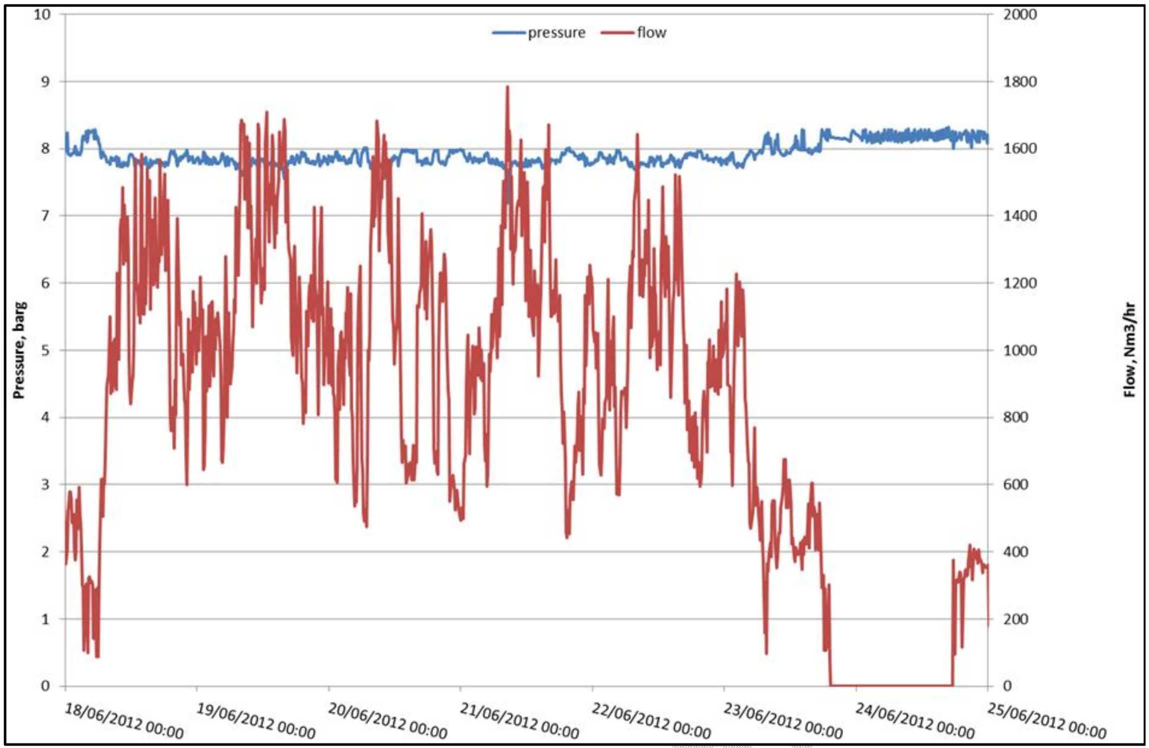

Figure 1: System demand and pressure during normal week

The figure 1 shows an average demand of around 1000Nm^3/hr during week time production, dropping to half this on Saturday when there is limited production. The peak demand is around 1800Nm^3/hr, which can bring in the compressor 2, although this varies each week. The system is isolated once production finishes around 18:00 on Saturday and is off for approximately 36 hours.

During shutdown periods (in August for example), the demand is much lower and can be met by one of the 55kW machines (i.e., compressor 2 or 3) as seen in figure 2. Over a year the average demand when the main compressors are running is around 750 Nm^3/hr.

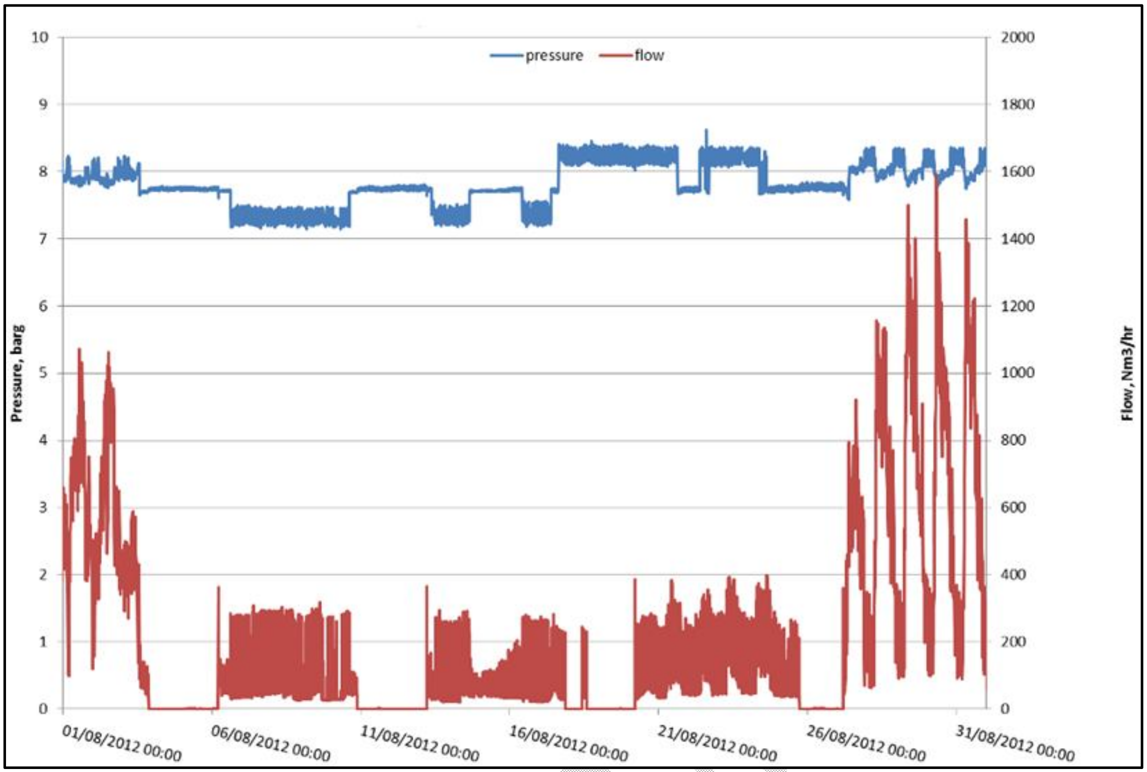

Figure 2: System demand and pressure during site shutdown

The flowmeter appears to be reading higher than it should. The VSD compressor has a rated output of around 1500 m^3/hourr yet the flowmeter shows readings of up to 1700 Nm^3/hr with just the one compressor online. It is thought that this is due to the installation, which is fairly close to a bend, the manufacturers recommend 20 diameters of straight pipe before the flowmeter is installed, in this case it is only around 5-6. The installation is shown in figure 3.

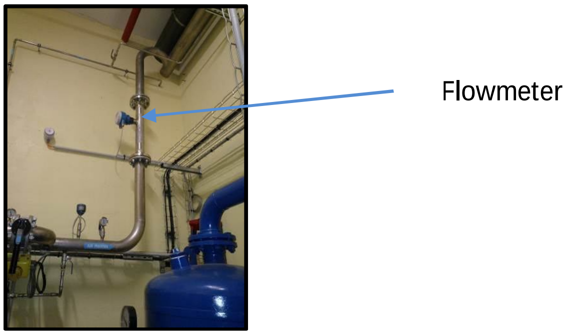

Figure 3: Flowmeter position

Presentation and analysis of air treatment system

The installed equipment is as follow for drying step:

- 1 heat regenerated desiccant dryer; Rated flow, m^3/hr = 2250; main dryer
- 1 Air regenerated desiccant; Rated flow, m^3/hr = 1650; back-up dryer

The installed equipment is as follow for filtering step:

- 1 Prefilter: Protect the network from particles. Efficacity = 99.999% until 0.01 µm.
- 1 After filter: it's a carbon active filter, it stops oil vapours, tastes, and smells up to 0.003 mg/m3
- 1 Sterile after filter: ensuring a very efficient filtration, because it stops particles, organisms, liquid aerosols and, dust resulting from the abrasion of the dryer's alumina balls. Efficacity = 99.99998% until 0.01 µm

In order to check the drop pressure across the treatment system a pressure transducer is in place downstream of the final filter. Due to the pipework configuration, it is impossible to measure before the prefilter but comparison to the compressor setpoint showed a maximum pressure drop of just 0.2 bar. This is acceptable.

The dryer is operating in dewpoint control (Baghban et al., 2016). The site energy monitoring system clearly shows a varying period between changeovers indicating this is working well. Analysing the annual kWh readings the dryer is consuming around 4% of the energy used by the duty VSD compressor. This is very low and indicates the dryer is running very efficiently. The dewpoint is monitored both on the dryer and externally using a site calibrated dewpoint meter. The results from this local meter are shown in figure (the spikes indicating when the towers changeover).

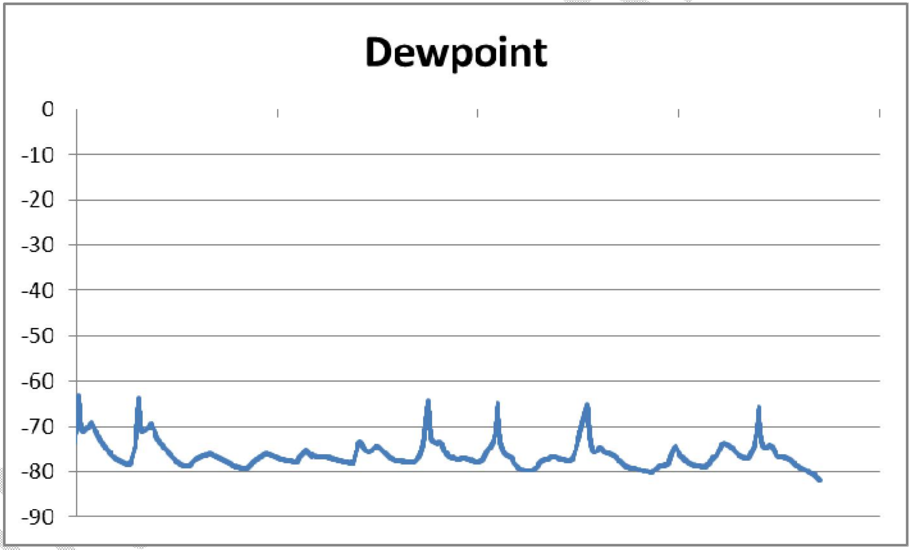

Figure 4: **Dewpoint (°C) results of the installation**

As seen in figure 5, the main dryer (2250m^3) is supplied with warm air from the compressor exhaust to feed the heater. This is a clever approach to heat recovery, although not applicable to all dryers as it needs a second cold air supply for cooling to allow this to work.

Warm air from compressor exhaust into dryer for heating

Figure 5: **Heat recovery between compressor and dryer**

Presentation and analysis of distribution system and using processes

Piping sizing and configuration

The piping network consists of 3 main systems:

- A galvanised system originally used to supply noncritical users
- A35NB stainless steel system installed in 2002 to supply critical class users
- A125/100NB stainless steel system installed in 2007 to supply the site

All three systems are located in the technical area above production. The systems have developed over the years as more users were transferred onto the higher quality system and production increased. Currently users are supplied from all three systems although they are gradually being transferred onto the large new bore system. All three systems form ring mains around the production areas. New stainless steel drop lines supply a lot of the using areas but there are also still many users fed from nylon lines coming down from the technical area.

The new system is comfortably large enough for the demand with a maximum velocity of below 5.5m/s at the peak demand if the entire load were on this system. 6m/s is the recommended maximum velocity for main distribution lines, although it can be significantly higher before pressure problems are seen. Unfortunately, a lot of the demand is still on the small old system. So, in order to check how this line is coping, the pressure is monitored at two points at the end of the manufacturing and packing areas and results are shown in figure 5 and 6.

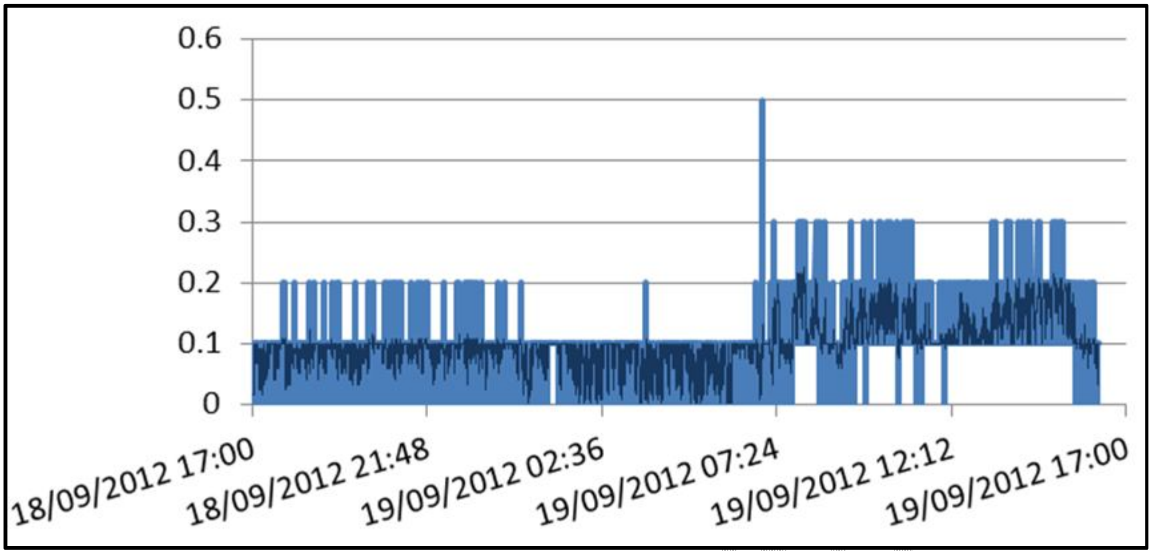

Figure 6: **Pressure drop from compressor room to packaging area**

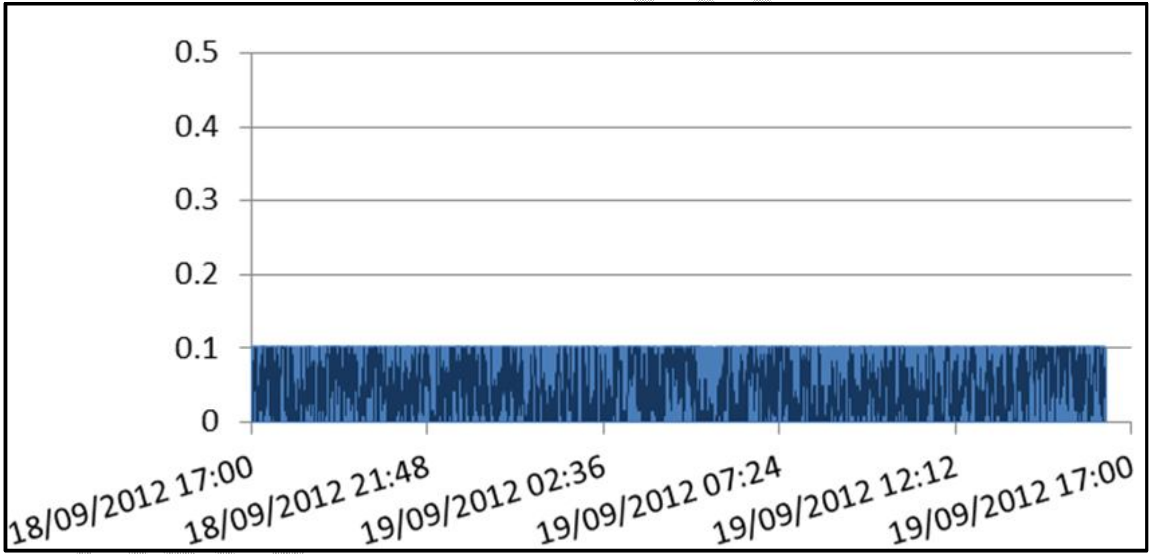

Figure 7: **Pressure drop from compressor room to manufacturing area**

The results in figure 6 show a maximum 0.2 bar pressure drop. This is just on the limit of good practice. As the readings were taken during a period of low production levels and hence low demand, they indicate that the work being done to transfer users from the small 2002 system to the new larger stainless-steel system is important. Also, by having three systems, it is difficult to properly isolate the packaging lines as there are several feeds into each line. This has a potential health and safety impact.

As seen in figure 7, the pressure drop to the making department is less than 0.1 bar.

Production line air isolation and vacuum usage

Leaks are a part of every air system but if not regularly repaired will continue to grow and become an unacceptably high usage (Abela et al., 2021). The normally accepted target for leaks is between 5 and 10% of demand. To assess leakage levels and identify potential savings an ultrasonic leak detection survey was undertaken (Soylu et al., 2022; M'Baye, 2022a). Leaks found were identified and rated on a scale of 1-10 as shown in table 3.

Table 3: Production line air isolation and vacuum usage

Scale	Estimated loss (cfm)		Estimated loss (m3/hr)		Cost of leak (€)	
-	min	Max	Min	max	Min	max
1	0.01	0.50	0.02	0.81	0.98	48.89
2	0.50	1.50	0.81	2.42	48.89	146.66
3	1.50	2.50	2.42	4.03	146.66	244.44
4	2.50	4.00	4.03	6.44	244.44	391.10
5	4.00	6.00	6.44	9.66	391.10	586.66
6	6.00	8.00	9.66	12.88	586.66	782.21
7	8.00	10.00	12.88	16.11	782.21	977.76
8	10.00	15.00	16.11	24.16	977.76	1466.64
9	15.00	25.00	24.16	40.27	1466.64	2444.40
10	25.00	100.00	40.27	161.06	2444.40	9777.60

The above costs are based on running 7200 hours per year at a cost of 0.07€/kWh.
All leaks identified rated at 2 or more should be addressed urgently. Leaks rated at 1 should be carefully watched as they will increase over time and should then be rectified.

16 leaks have been identified with a maximum potential loss of 33 cfm, 56 m^3/hr. This is quite a small number of leaks and shows the main areas are well maintained. The leaks distribution per area is indicated in table 4.

Table 4: The leaks distribution per area

Area	Number Of Leaks	Estimated loss		Estimated Cost pa
		cfm	m^3/hr	€
Technical area	3	8	13	782.21
Packaging	5	10.5	17	1026.65
Manufacturing	5	10	16	977.76
Dedusters	3	4.5	7	439.99

Total	16	33	53	2790.84

The leaks were mainly small, as would be expected, with just 2 rated over 3 (one of which was easily repaired during the survey). The distribution is as shown in figure 8.

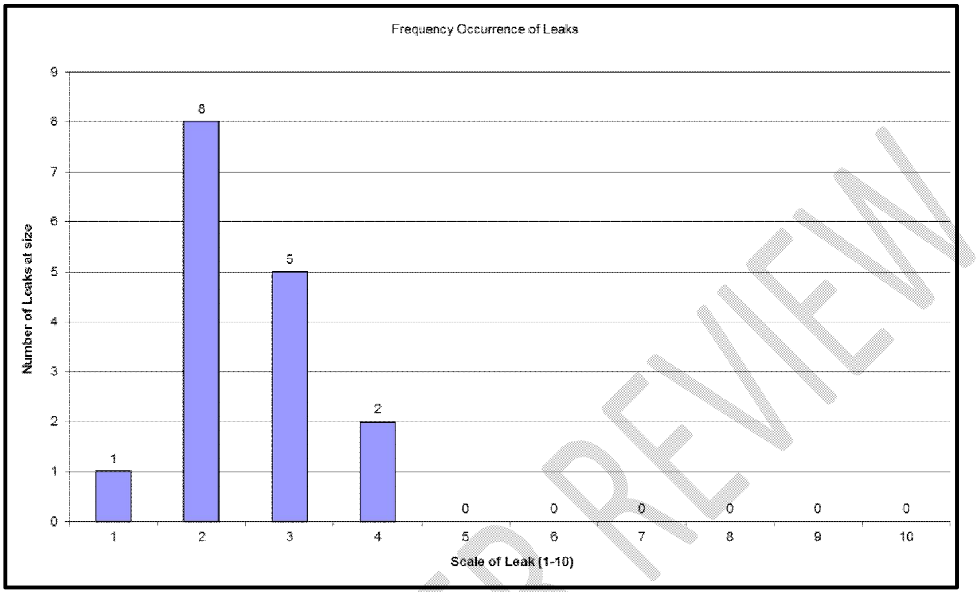

Figure 8: Frequency occurrence of leaks

Reducing the demand by 56 m3/hr would save 2800€.
The purchase of an ultrasonic leak detector should be considered, and leak surveys and rectification should be conducted every three to six months. Alternatively, it may be acceptable to carry out checks by ear at weekends when the plant is quiet.

In order to reduce wastage a shutdown procedure should be developed for each production line (M'Baye, 2022b). This should ensure all equipment, including compressed air, motors etc. are shut off when the machine is not in use.

Moreover, the lines should be fitted with automatic isolation valves so that air to the entire line is shutdown when the line is stopped.

It was also noted that 10 of the 11 packaging lines had venturi vacuum systems. The efficiency of these can vary considerably and for a continually running system it can cost up to 10 times more to run a venturi system than a dedicated electric vacuum pump (Singhal, 2007). Compressed air venturi vacuum devices must be replaced by electrically driven vacuum pumps. The machine manufacturers should be consulted, along with vacuum pump suppliers.
Based on an estimated vacuum demand of around 15m3/hr per line, it has been calculated a saving of over 4450€ per year by switching to electrically operated vacuum pumps (assuming running around 50% of the time).

When converting vacuum systems, it is necessary to ensure that the draw down times are still suitable for the application. The use of vacuum pumps will increase heat into the area and may have a detrimental effect on the HVAC (Heating Ventilation Air Conditioning) energy usage if located in the production area.

Heat recovery

Heat recovery on compressed air (either cooled by air or water) is possible and the principle is similar to heat recovery thanks to a heat pump (M'Baye, 2022c) and internal combustion engine (Saidur et al., 2012b). The potential to recover heat from air cooled machines is predominantly ducting the hot exhaust air for space heating.

The site of this case study has 2 warehouses that need heating. The practicality of ducting the hot air into the adjacent warehouses is not good. In fact, there are critical products in those warehouses (air must be treated to meet requirement) and there is no clear route for the ducting as there are toilets and offices immediately adjacent to the compressor house wall. Nevertheless, it is possible to recover some heat for hot water by installing a heat exchanger in the exit duct. Figure 9 is an example of such installation (heat recovery on a fixed speed compressor that provides a continuous heat load and can provide water temperatures of over 35°C).

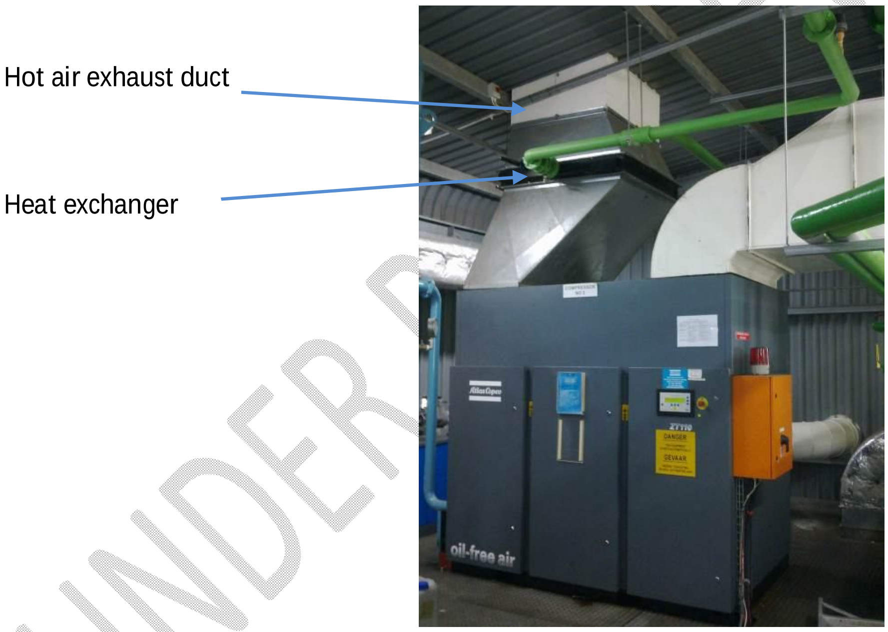

Figure 9: Example of heat recovery on a compressed air to produce hot water thanks to an exchanger

In this case study, the heat available is much more varied (as the load is variable). During daytime production temperatures measured in the exhaust air duct are low, at times less than 35°C, increasing to nearer 50°C at higher loads. There is also no obvious use for warm water, the boilers are close but with return temperatures of close to 75°C they would not be able to utilise such low-grade heat.

This heat could be used for preheating the water in the washing room or directly for preheating the water destinated to the domestic hot water (simpler solution and maximum recovery). Needs identified: Washing room = 347 MWh/year; Domestic Hot Water = 400 MWh/year

As stated before, a proportion of the hot exhaust air is recovered for use in the dryer regeneration cycle. Although this does not use much of the compressor heat available, it is a good practice and will help keep the dryer running costs as low as possible.

Smart management device

There is currently no intelligence in the operation of compressors related to energy management.

Compressors 2 and 3 run only when there is an additional flow demand (no routine start). There is also no centralization and digitization of compressed air system information related to maintenance plans.

The installation of a smart box will centralize the operation, energy management and data monitoring of the compressed air system through (Nehler, 20218):

- Intelligent compressor start-up
    - Algorithm for improving energy consumption (i.e., operating the "compressor mix" in the most ecological and economical way possible)
    - Automatic start of the compressors which are in backup (increased reliability of compressed air production)
- Centralization of compressed air system information
    - connection with the BMS
    - Management of remote alarms / on-condition indicators
    - Single point of monitoring for maintenance
    - Centralization of set points

Figure 10: Sigma Air manager® by Kaiser

This equipment will also simplify maintenance tasks: Digital recording of information, remote monitoring of information and no need for routine maintenance for the device (except annual calibration).

In case of failure of the smart box, the compressors will be autonomous, and the alarms will be managed by the BMS (production of compressed air always ensured).

Action plan summary

The recommendations are listed in table 5. There are prioritised, reflecting a balance between the time to implement, estimated cost to implement and savings expected.

Table 5: recommendations summary

Priority	Recommended Actions	Summary				
		Estimated annual savings			Estimated cost	Payback period (years)
		€	kWh	CO$_2$ (tonnes)	€	
1	Reduce leaks	2623	37474	3.11	2400	0.9
2	Reduce system pressure	1849	26411	2.19	0	0.0
3	Isolate packaging lines when stopped	11131	159010	13.20	55,200	5.0
4	Increase efficiency of vacuum generation on packaging lines	4469	63840	5.30	18000	4.0

Priority	Recommended Actions	Summary				
		Estimated annual savings			Estimated cost	Payback period (years)
		€	kWh	CO_2 (tonnes)	€	
5	Implement smart management device	14336	321126	26.65	24000	1.7
6	Heat recovery	10000	224,000	18.59	32,000	3.2
-	**Total**	44408	631296	69.04	131600	2.47

Conclusion

The decarbonization of industry involves optimizing the consumption of compressed air on industrial sites.

Several and different recommended actions have been identified through a thorough analysis of the installation of this case study. New technology and innovation have also been taken into consideration.

The total savings identified are up to 69 tons of CO2. At the same time, substantial financial savings have been identified (up to 44 k€)

Once consumption has been optimized, the next step is to supply the equipment with renewable energy (solar panels, wind turbines, etc.).

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