

# A case study on sustainable production and use of compressed air in European industrial sites of medium-sized

## **Abstract**

Due to the urgency in climate change, the industry is mobilized to reduce its greenhouse gases. Compressed air represents nearly 10% of electricity used in industry. The research was carried out in an industrial food site in Europe. This research includes a case study and gives a specific approach and methodology to optimize environmental and economic impact of compressed air production and uses in an industrial site. The installation of this case study contains different type of compressed air, dryers, and filters. Each equipment has been subject to specific monitoring and analysis. Several actions have been identified for reducing carbon emissions by 69 tons such as: reduction of the compressed air pressure of the system, isolation of packaging lines when they are not running, implementation of pumps for vacuum generation on packaging lines, installation of smart management device and a heat recovery system. Financial savings are around 44 000 euros, and the average payback is below 3 years.

## **Introduction**

Global energy consumption has doubled over the past four decades, and this trend will continue with an average annual increase of 1.5% in the period from 2018 to 2050 (Herrera et al., 2021).

Compressed air is an energy widely used in the industrial sector and companies continuously seek process to decarbonize it (Byun et al., 2022). 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 (Herrera et al., 2020). Compressed air is also used for energy storage technology and received increasing attention in addressing the issue of intermittent renewable energy (Lu, 2023).

Compressed air represents nearly 10% of electricity used in industry (Widayati&Nuzahar, 2016; Cabello et al., 2020). 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). According to Çağman et al. (2022), a compressed air system can use only 10–30% of the consumed energy to produce compressed air and therefore compressed air systems are classified as the most inefficient systems energized by electricity regarding high energy consumption.

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 (Shannon, 2018).

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.

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

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

## 42 **Material & Methods**

### 43 *The compressed air installation*

44 Compressed air is generated at a central location on the industrial site to supply air at around 8 barg  
45 for process and instrumentation purposes to all areas of the site. Figure 1 represents the whole  
46 system in a schematic diagram.

47

48 The air is generated by three air cooled, two stages, and oil free rotary screw compressors. One of the  
49 compressors is fitted with a variable speed drive (VSD). The two standby units are 55kW with a  
50 160kW duty VSD which runs all week. Once production finishes on a Saturday afternoon the system  
51 is isolated, and a small 2kW compressor is used solely to supply permanently operating equipment  
52 such as cooling towers. The compressors are controlled from their individual pressure switches with  
53 no central controller.

54

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

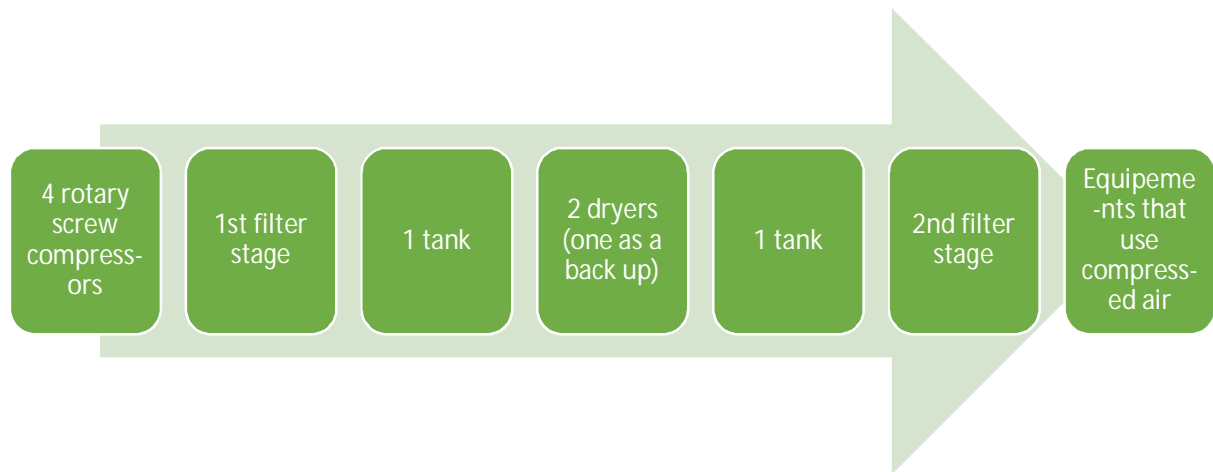
58 Compressed air is stored in two 2000 liter tanks (1 tank before dryers and 1 tank after dryers) to  
59 prevent high and variable pressure differential.

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

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

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

71



**Figure 1: Schematic diagram of the compressed air system**

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Compressors' performance analysis

76 The table 1 contains the main settings of the compressors.

77 **Table 1:**

Compressor number	Type	Rated output (m <sup>3</sup> /h)	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	-

78

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

- 81 • Time at 0 -20% speed → 0%
- 82 • Time at 20 – 40% speed → 35%
- 83 • Time at 40 – 60% speed → 36%
- 84 • Time at 60 – 80% speed → 25%
- 85 • Time at 80 – 100% speed → 4%

86

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

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

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

93 **Table 2:**

<b>Parameter</b>	<b>Reading</b>
Speed	3200 rpm
Discharge pressure	7.9 barg
Inlet filter differential pressure	0.003 barg
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

94

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

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

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

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System demand measurement

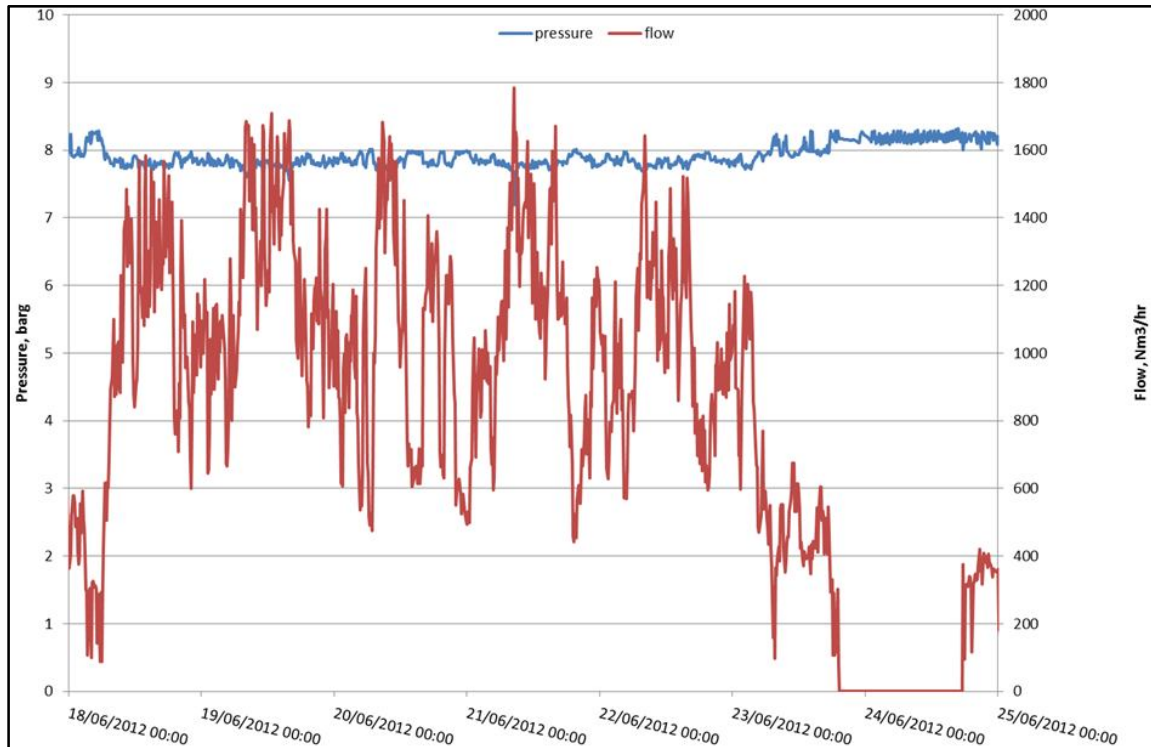
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The system demand is measured using an Endress & Hauser Mass flowmeter. The demand pattern

105

across a typical full production week is represented in figure 2.

106



107

**Figure 2: System demand and pressure during normal week**

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The figure 2 shows an average demand of around 1000Nm<sup>3</sup>/h during week time production, dropping

110

to half this on Saturday when there is limited production. The peak demand is around 1800Nm<sup>3</sup>/h,

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which can bring in the compressor 2, although this varies each week. The system is isolated once

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production finishes around 18:00 on Saturday and is off for approximately 36 hours.

113

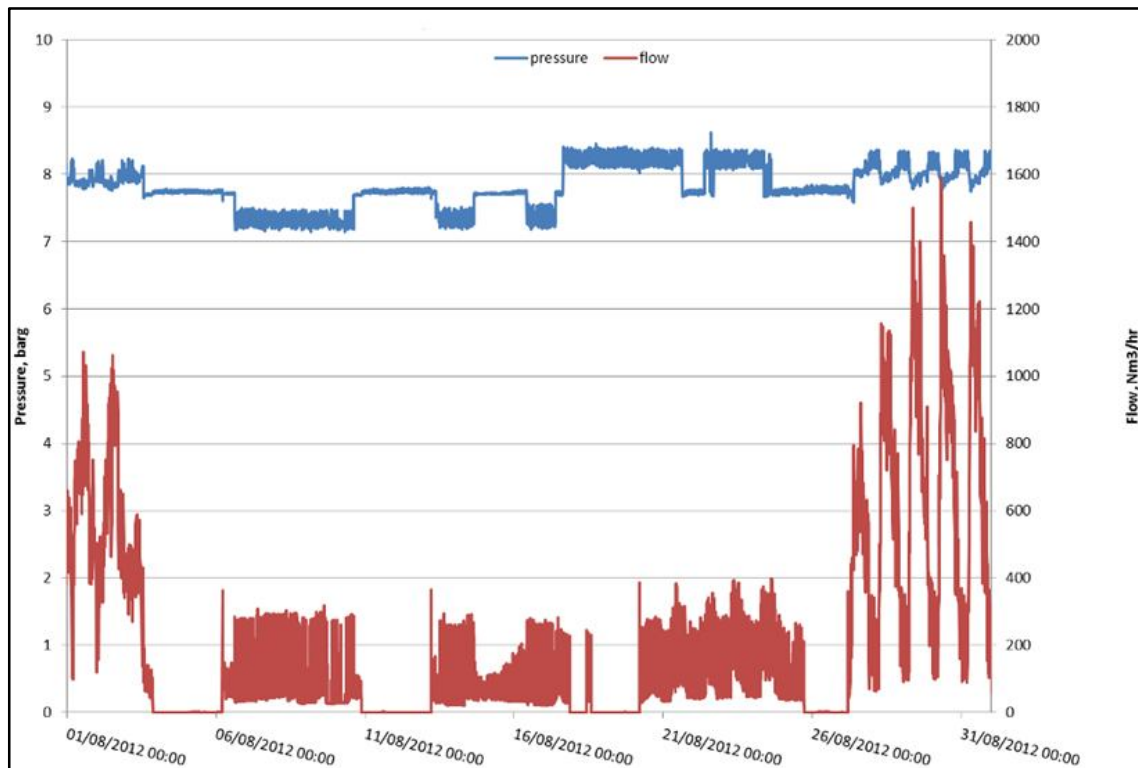
During shutdown periods (in August for example), the demand is much lower and can be met by one

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of the 55kW machines (i.e., compressor 2 or 3) as seen in figure 3. Over a year the average demand

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when the main compressors are running is around 750 Nm<sup>3</sup>/h.



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**Figure 3: System demand and pressure during site shutdown**

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119 The flowmeter appears to be reading higher than it should. The VSD compressor has a rated output  
 120 of around 1500 m<sup>3</sup>/h but the flowmeter shows readings of up to 1700 Nm<sup>3</sup>/h (with just the VSD  
 121 compressor online). It is thought that this is due to the location of the flowmeter, which is fairly close  
 122 to a bend. The manufacturer recommends 20 diameters of straight pipe before and after the  
 123 flowmeter. In this case, it is only around 5 to 6 diameters. The location of the flowmeter is shown in  
 124 figure 4.



**Figure 4: Compressed air flowmeter location**

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126

127 Presentation and analysis of air treatment system

128 Installed equipment for the drying step:

- 129 • 1 heat regenerated desiccant dryer; Rated flow= 2250m<sup>3</sup>/h; Main dryer
- 130 • 1 Air regenerated desiccant dryer; Rated flow= 1650m<sup>3</sup>/h; Back-up dryer

131

132 Installed equipment for the filtering step:

- 133 • 1 Prefilter: Protect the network from particles. Efficiency = 99.999% until 0.01 μm.
- 134 • 1 After filter: It's a carbon active filter. It stops oil vapours, tastes, and smells up to 0.003mg/m<sup>3</sup>
- 135
- 136 • 1 Sterile after filter: Ensure a very efficient filtration, because it stops particles, organisms, liquid aerosols and, dust resulting from the abrasion of the dryer's alumina balls. Efficiency =
- 137 99.99998% until 0.01 μm
- 138

139

140 In order to check the drop pressure across the treatment system a pressure transducer is in place  
 141 downstream of the final filter. Due to the pipework configuration, it is impossible to measure before  
 142 the prefilter but comparison to the compressor setpoint showed a maximum pressure drop of just  
 143 0.2 barg. This is acceptable.

144

145 Presentation and analysis of distribution system

146 The piping network consists of 3 main systems:

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

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

156 Production lines air isolation and vacuum usage

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

162 **Table 3:**

Scale	Estimated loss (cfm = Cubic feet per minute)		Estimated loss (m <sup>3</sup> /h)		Cost of a leak (€)	
	min	Max	Min	max	Min	max
-						
A	0.01	0.50	0.02	0.81	0.98	48.89
B	0.50	1.50	0.81	2.42	48.89	146.66
C	1.50	2.50	2.42	4.03	146.66	244.44
D	2.50	4.00	4.03	6.44	244.44	391.10
I	4.00	6.00	6.44	9.66	391.10	586.66
F	6.00	8.00	9.66	12.88	586.66	782.21
G	8.00	10.00	12.88	16.11	782.21	977.76
H	10.00	15.00	16.11	24.16	977.76	1466.64
I	15.00	25.00	24.16	40.27	1466.64	2444.40
J	25.00	100.00	40.27	161.06	2444.40	9777.60

163 The above costs are based on running 7200 hours per year at a cost of 0.07€/kWh.

164 All leaks identified rated B or more should be addressed urgently. Leaks rated A should be carefully  
 165 watched as they will increase over time and should then be rectified.

166  
 167

168

Partial heat recovery

169 As seen in figure 5, the heater of the main dryer (2250m<sup>3</sup>) is supplied with warm air from the  
170 compressor exhaust. This is a clever approach to recover heat, although it is not applicable to all  
171 dryers as it needs a second cold air supply for cooling.

172



Warm air from  
compressor exhaust  
into dryer for heating

173

174

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

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176

177 **Results & Discussions**

178 Pressure functioning

179 The compressors are controlled from their individual pressure switches. At the start of the research  
180 the settings were as follows:

- 181 • Compressor 1 = 7.9 barg
- 182 • Compressor 2 = 7.5-7.6 barg
- 183 • Compressor 3 = 6.4 -6.9 barg

184  
185 The settings on the fixed speed have been manually made to ensure the VSD stays on load. The  
186 compressor 3 setting is for emergencies only and is not considered a reasonable running pressure  
187 during production.

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

191  
192 During the research the pressures were reset as follows (immediate action):

- 193 • Compressor 1 = 7.3 barg
- 194 • Compressor 2 = 7.0-7.5 barg
- 195 • Compressor 3 = 6.4 – 6.9 barg

196  
197 According to Vittorini and Cipollone (2017), a 1 barg reduction, from an 8 barg pressure ratio leads to  
198 a 10% saving and the higher the delivered pressure, the lower the benefit: at 15 barg delivery  
199 pressure, the 1 barg reduction leads to a 4% saving.

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

206 The average specific power consumption has been reduced from 12.66 to 12.25 kW/100Nm<sup>3</sup>/h. The  
207 figure of 7.3 barg was chosen as a safe level and it is likely that the pressure can be reduced further.

208 A new set up can be put in place as long as there is no risk to production (i.e., pressure to production  
209 machines is maintained at a suitable level).

210  
211 In addition to power consumption decrease at a set flow, pressure reduction also increases the  
212 maximum output from the compressor 1 (VSD). At 7 barg the maximum speed is 4300 rpm, dropping  
213 to 4020 rpm at 8.6 barg. The change from 7.9 to 7.3 barg should have increased output by around  
214 40m<sup>3</sup>/h.

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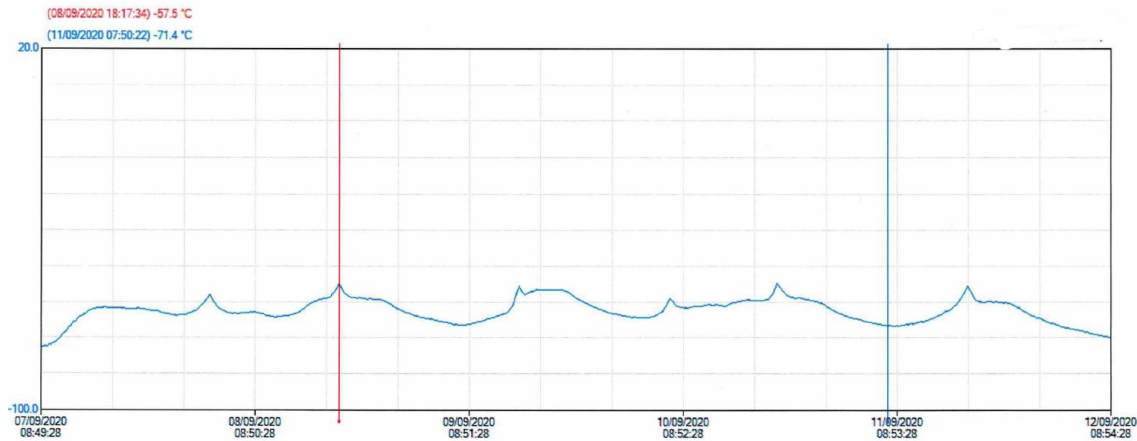
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### Compressed air drying

220 The dryer is operating in dewpoint control (Baghban et al., 2016). The site energy monitoring system  
221 clearly shows a varying period between changeovers indicating that the dryer is working well. Based  
222 on electrical meter in place, the dryer is consuming around 4% of the energy used by the duty VSD  
223 compressor. This is very low and indicates the dryer is running very efficiently. The dewpoint is  
224 monitored both on the dryer and externally using a site calibrated dewpoint meter. The results from  
225 this local meter are shown in figure 6 (the spikes indicating when the towers changeover).



226

**Figure 6: Dewpoint of the installation – Y axis unit = °C and X axis unit = date & hour**

227

228

229

### Compressed air loops

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

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

241 The monitoring in the manufacturing department shows a pressure drop that is less than 0.1 bar.

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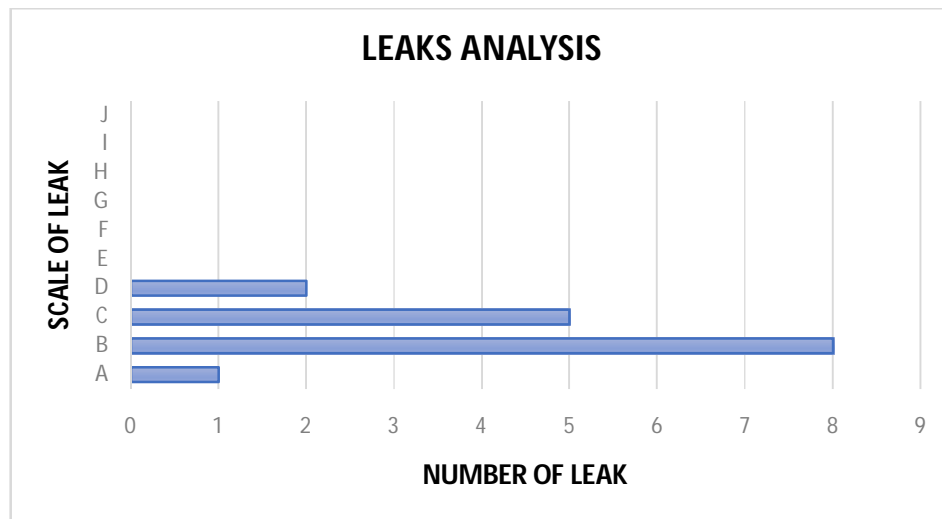
245 Compressed air leaks

246 16 leaks have been identified with a maximum potential loss of 33 cfm, 56 m<sup>3</sup>/h. This is quite a small  
247 number of leaks and shows the main areas are well maintained. The leaks distribution per area is  
248 indicated in table 4.

249 **Table 4:**

Area	Leaks number	Estimated loss		Estimated Cost pa
		cfm	m <sup>3</sup> /h	€
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

250  
251 The leaks were mainly small, as would be expected, with just 2 rated over 3 (one of which was easily  
252 repaired during the survey). The distribution is as shown in figure 7.  
253  
254



255 **Figure 7:Leaks analysis (size and number)**

256  
257 Reducing the demand by 56 m<sup>3</sup>/h would save 2800€.  
258 The purchase of an ultrasonic leak detector should be considered, and leak surveys and rectification  
259 should be conducted every three to six months. Alternatively, it may be acceptable to carry out  
260 checks by ear at weekends when the plant is quiet.  
261  
262 In order to reduce wastage a shutdown procedure should be developed for each production line  
263 (M'Baye, 2022b). This should ensure all equipment, including compressed air, motors etc. are shut  
264 off when the machine is not in use.  
265

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

### 268 Vacuum systems

269 It was also noted that 10 of the 11 packaging lines had venturi vacuum systems. The efficiency of  
270 these can vary considerably and for a continually running system it can cost up to 10 times more to  
271 run a venturi system than a dedicated electric vacuum pump (Singhal, 2007). Compressed air venturi  
272 vacuum devices must be replaced by electrically driven vacuum pumps. The machine manufacturers  
273 should be consulted, along with vacuum pump suppliers.

274 Based on an estimated vacuum demand of around 15m<sup>3</sup>/h per line, it has been calculated a saving of  
275 over 4450€ per year by switching to electrically operated vacuum pumps (assuming running around  
276 50% of the time).

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

281

### 282 Smart management device

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

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

287 The installation of a smart box like the one represented in figure 8 will centralize the operation,  
288 energy management and data monitoring of the compressed air system through (Nehler, 20218):

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



299

300

**Figure 8: Sigma Air manager® by Kaiser**

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

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

306

307 Total heat recovery

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

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

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Hot air exhaust duct

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326

Heat exchanger

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328

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333

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

334

335

336

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.

341

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

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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.

345

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348

Actions plan summary

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

351 **Table 5:**

Priority	Recommended Actions	Summary				
		Estimated annual savings			Estimated cost	Payback period (years)
		€	kWh	CO <sub>2</sub> (tonnes)	€	
1	Reduce leaks	2623	37474	3.11	2400	0.9
2	Reduce system demand pressure	1849	26411	2.19	0	0.0
3	Isolate packaging lines when stopped	11131	159010	13.20	55200	5.0
4	Increase efficiency of vacuum generation on packaging lines	4469	63840	5.30	18000	4.0
5	Implement smart management device	14336	321126	26.65	24000	1.7
6	Heat recovery	10000	224000	18.59	32000	3.2
-	<b>Total</b>	44408	631296	69.04	131600	2.47

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354

355 **Conclusion**

356 In summary, the decarbonisation process in industries requires several stages and the consumption  
357 of new materials for complete optimization with the use of compressed air on industrial sites. New  
358 technology and innovation have also been taken into consideration. The total savings identified are  
359 up to 69 tons of CO<sub>2</sub> gas. At the same time, substantial financial savings have been identified (up to  
360 44 k€). Once consumption has been optimized, the next step is to supply the equipment with  
361 renewable energy such as solar panels and wind turbines. However, we must not completely  
362 disregard the risk factor for accidents involved, as well as the safety of the environment, bodies of  
363 water, and human workers involved near the systems under high pressure (minimum 4 barg).

364 **References**

365 Abela Kyle, Refalo Paul, Francalanza Emmanuel, Analysis of pneumatic parameters to identify  
366 leakages and faults on the demand side of a compressed air system, Cleaner Engineering and  
367 Technology, Volume 6, 2022, 100355, ISSN 2666-7908, <https://doi.org/10.1016/j.clet.2021.100355>

368 BaghbanAlireza, BahadoriMohammad, RozynJake, LeeMoonyong, AbbasAli, BahadoriAlireza,  
369 RahimaliArash, Estimation of air dew point temperature using computational intelligence schemes,  
370 Applied Thermal Engineering, Volume 93, 2016, Pages 1043-1052, ISSN 1359-4311,  
371 <https://doi.org/10.1016/j.applthermaleng.2015.10.056>

372 ByunManhee, LimDongjun, LeeBoreum, KimAyeon, Lee In-Beum, Brigljević Boris, LimHankwon,  
373 Economically feasible decarbonization of the Haber-Bosch process through supercritical CO<sub>2</sub> Allam  
374 cycle integration, Applied Energy, Volume 307, 2022, 118183, ISSN 0306-2619,  
375 <https://doi.org/10.1016/j.apenergy.2021.118183>

376 Cabello Eras Juan José, Sagastume Gutiérrez Alexis, Sousa Santos Vladimir, Cabello Ulloa Mario  
377 Javier, Energy management of compressed air systems. Assessing the production and use of  
378 compressed air in industry, Energy, Volume 213, 2020, 118662, ISSN 0360-5442,  
379 <https://doi.org/10.1016/j.energy.2020.118662>

380 Çağman Selman, SoyluEren, ÜnverÜmit, A research on the easy-to-use energy efficiency performance  
381 indicators for energy audit and energy monitoring of industrial compressed air systems, Journal of  
382 Cleaner Production,- Volume 365, 2022, 132698,ISSN 0959-  
383 6526,<https://doi.org/10.1016/j.jclepro.2022.132698>.

384 Giampieri A., Ling-Chin J., Ma Z., Smallbone A., Roskilly A.P., A review of the current automotive  
385 manufacturing practice from an energy perspective, Applied Energy, Volume 261, 2020, 114074, ISSN  
386 0306-2619, <https://doi.org/10.1016/j.apenergy.2019.114074>

387 Grande-Acosta Genice, Islas-Samperio Jorge, Towards a low-carbon electric power system in Mexico,  
388 Energy for Sustainable Development, Volume 37, 2017, Pages 99-109, ISSN 0973-0826,  
389 <https://doi.org/10.1016/j.esd.2017.02.001>

390 Herrera, H. H., Silva-Ortega, J. I., Diaz, V. L. M., Pons, A. G., & Sanchez, Z. G. (2020, May). Potential  
391 Energy savings in compressed air systems in industrialized cities. A case study in Barranquilla and  
392 Cartagena. In IOP Conference Series: Materials Science and Engineering (Vol. 844, No. 1, p. 012019).  
393 IOP Publishing. <https://doi.org/10.1088/1757-899X/844/1/012019>

394 Herrera, H. H., Villalba, D. P., Angarita, E. N., Ortega, J. S., & Echavarría, C. C. (2021, June). Energy  
395 savings in compressed air systems a case of study. In IOP Conference Series: Materials Science and  
396 Engineering (Vol. 1154, No. 1, p. 012009). IOP Publishing. [https://doi.org/10.1088/1757-](https://doi.org/10.1088/1757-899X/1154/1/012009)  
397 [899X/1154/1/012009](https://doi.org/10.1088/1757-899X/1154/1/012009)

398 Lu Zisheng, Experimental analysis of one micro-compressed air energy storage-power generation  
399 system with different working fluids, Journal of Energy Storage, Volume 60, 2023, 106647, ISSN 2352-  
400 152X, <https://doi.org/10.1016/j.est.2023.106647>

401 Mbaye, A. (2022a). Review on Energy Audit: Benefits, Barriers, and Opportunities. American Journal  
402 of Energy and Natural Resources, 1(1), 45–58. <https://doi.org/10.54536/ajenr.v1i1.1054>

403 M'baye, A. (2022b). Carbon Emission Efficiency Best Practices: A Case Study in an Industrial Site.  
404 Journal of Energy Research and Reviews, 10(3), 10–23.  
405 <https://doi.org/10.9734/jenrr/2022/v10i330256>

406 M'Baye, A. (2022c). A case study of heat recovery: a heat pump in an industrial site. Renewable  
407 Energy and Sustainable Development, 8. <http://dx.doi.org/10.21622/resd.2022.08.1.020>

408 MousaviSmaeil, Kara Sami, Kornfeld Bernard, Energy Efficiency of Compressed Air Systems, Procedia  
409 CIRP, Volume 15, 2014, Pages 313-318, ISSN 2212-8271,  
410 <https://doi.org/10.1016/j.procir.2014.06.026>

411 Nehler Therese, Linking energy efficiency measures in industrial compressed air systems with non-  
412 energy benefits – A review, Renewable and Sustainable Energy Reviews, Volume 89, 2018, Pages 72-  
413 87, ISSN 1364-0321, <https://doi.org/10.1016/j.rser.2018.02.018>

414 Saidur R., Rahim N.A., Hasanuzzaman M., A review on compressed-air energy use and energy savings,  
415 Renewable and Sustainable Energy Reviews, Volume 14, Issue 4, 2010, Pages 1135-1153, ISSN 1364-  
416 0321, <https://doi.org/10.1016/j.rser.2009.11.013>

417 Saidur R., Mekhilef S., Ali M.B., Safari A., Mohammed H.A., Applications of variable speed drive (VSD)  
418 in electrical motors energy savings, Renewable and Sustainable Energy Reviews, Volume 16, Issue 1,  
419 2012a, Pages 543-550, ISSN 1364-0321, <https://doi.org/10.1016/j.rser.2011.08.020>

420 Saidur R., Rezaei M., Muzammil W.K., Hassan M.H., Paria S., Hasanuzzaman M., Technologies to  
421 recover exhaust heat from internal combustion engines, Renewable and Sustainable Energy Reviews,  
422 volume 16, Issue 8, 2012b, Pages 5649-5659, ISSN 1364-0321,  
423 <https://doi.org/10.1016/j.rser.2012.05.018>

424 Shannon, Tommy (2018) "A Case Study of Energy Efficient Measures Undertaken in an Industrial  
425 Facility," SDAR\* Journal of Sustainable Design & Applied Research: Vol. 6: Iss. 1, Article 3. doi:  
426 <https://doi.org/10.21427/D74C07>

427 Singhal, D. K. (2007). Energy Audit of Vacuum System. IPPTA, 19(2),  
428 129. <https://doi.org/10.21427/D74C07>

429 Soylu E., Bilgin H., Cagman S. and Unver U., "An Ultrasonic Application to Evaluate Energy Costs of Air  
430 Leakages at the Compressed Air Systems," 2021 6th International Conference on Smart and

- 431 SustainableTechnologies (SpliTech), Bol and Split, Croatia, 2021, pp. 1-3, doi:  
432 <https://doi.org/10.23919/SpliTech52315.2021.9566418>
- 433 Trianni Andrea, Cagno Enrico, Accordini Davide, Energy efficiency measures in electric motors  
434 systems: A novel classification highlighting specific implications in their adoption, Applied Energy,  
435 Volume 252, 2019, 113481,ISSN 0306-2619,<https://doi.org/10.1016/j.apenergy.2019.113481>
- 436 Vittorini, D., &Cipollone, R. (2017, August). Carbon and Energy Saving Financial Opportunities in the  
437 Industrial Compressed Air Sector. In IOP Conference Series: Materials Science and Engineering (Vol.  
438 232, No. 1, p. 012085). IOP Publishing. <https://doi.org/10.1088/1757-899X/232/1/012085>
- 439 WidayatiEndangand NuzaharHasril, 201, IOP Conf. Ser.: Mater. Sci. Eng. 105 012018, [https://doi.org/](https://doi.org/10.1088/1757-899X/105/1/012018)  
440 [10.1088/1757-899X/105/1/012018](https://doi.org/10.1088/1757-899X/105/1/012018)
- 441