Air Compressor System Energy Efficiency Optimization Management and Technical Guide

The six most important points for compressed air system optimization：

- Check the compressed air application and replacing it with more efficient alternative solutions if possible.
- Check compressed air application reasonable requirement: limit to the required pressure level. 1 bar lower network pressure results in 10% electricity saving.
- Use high efficient compressed air system equipment.
- Minimize system running time: switch off system at night and at weekends when no workload is needed.
- Systematically cut leaks in pipes, fittings, valves, connections and consuming end.
- Use demand-controlled efficient motor and use efficient and suitable air compressors: usage of a higher-level control

1. Introduction

1.1 Target and target audience

This compressed air system guideline deals with the subject of efficient compressed air systems. It provides information about efficient compressed air production and compressed air application in the planning of new plants as well as tips and know-how in the optimization of existing plants. It targets for all the technically interested audience, such as users, planners, installers and energy consultants etc.

1.2 Tasks of the participants

The design of an optimal compressed air supply system requires the interaction of several experts in different fields. The required air volume, network pressure as well as compressed air quality must be defined as precisely as possible at early stage. Subsequently, a planning company or compressor supplier creates a system concept that meets these requirements as meaningfully and economically as possible. After the implementation, internal employees are required to understand the system and can continuously adjust the operation if necessary. For example, switching to standby or off mode for a production-free holiday can save energy without too much effort. It is important to design the system precisely for all occurring requirements and to simulate the operating conditions in advance. In this case, oversizing must always be avoided in order to ensure an optimum operating point.

2. Compressed air system basics

Where and how are compressed air systems used wisely?

A distinction for air system is made between fan (up to 0.1 bar overpressure), blower (up to 3 bar overpressure) and compressor (from 3 bar overpressure). Because the compression of the air and the friction in the compressors which generates unavoidably large amounts of heat energy and is often not used, the energy consumption of the compression process is considerable. In addition to electricity, compressed air is an important secondary energy carrier in industry and manufacturing. With compressed air, many devices, machines and equipment are operated for cylinders to move and press, compressed air valves in pipelines, air motors (explosion protection), pneumatic tools, purge air to protect against contamination, blowing nozzles for cleaning, drying and cooling, injectors for material transport and to generate vacuum and to inflate.

In an ideal compressed air system, the compressor supplies exactly the required pressure and the required air volume for one specific application and at the rest of the time it is switched off. However, in the real compressed air system, many applications are connected to a distribution network and the compressor is set to operate at maximum required pressure of perhaps a single application. In addition, many machines leak compressed air from leaks even when they are not in operation, because the compressor is under operation not only during working hours but also during work-off hours. Figure 2 shows the simplest form of a compressed air system. It shows a hand-operated piston as a compressor and a pneumatic cylinder as an application. If air is compressed by the piston, the cylinder extends.

Figure 1 On the left is the compressed air pump (compressor), on the right is the compressed air cylinder (application).

2.1 Definitions

A compressed air system consists of:

- An electric motor as the drive
- A compressor that sucks and compresses outside air
- A storage tank
- A distribution network

- Application equipment, which use the compressed air energetically

Figure below shows compressor is a combination of motor, compressor and cooler.
A compressed air system compresses air to a smaller volume and thus generates pressure. The measure of the overpressure is the unit "bar". A compressor with 7 bar means it has an outlet pressure which is 7 bar greater than the atmospheric pressure (about 1 bar absolute, depending on the weather and altitude). Compared to the vacuum, the pressure is about 8 bar (absolute) or 800 kPa (kilo Pascal). The delivery quantity refers to the volume of air sucks in by the compressor. The variables are l/s (liters per second), l/min (liters per minute) and m^3/min (cubic meters per minute) and m^3/h (cubic meters per minute)

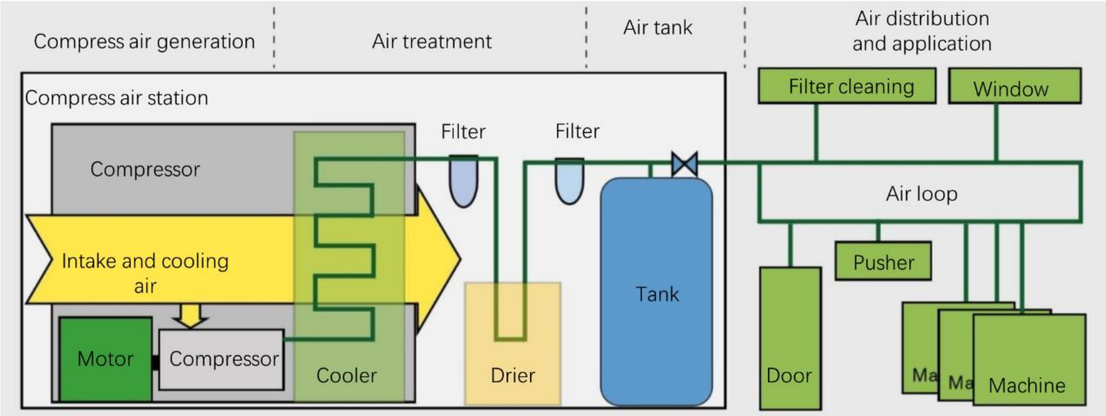

Figure 2 Components of a compressed air system (Source: Rolf Gloor)

Table 1 Overview of different pressure ranges

Absolute pressure		Over Pressure	Description
Pa	Bar	bar	
0	0	-1	Perfect vacuum
2 000	0.02	-0.98	Negative pressure of vacuum pumps
15 000	0.15	-0.85	Negative pressure of compressed air ejectors
50 000	0.5	-.05	Negative pressure of a suction fan
75 000	0.75	-0.25	Negative pressure of a vacuum cleaner
89 120	0.89	-0.11	Air pressure at 1000 m above sea level
100 000	1	0	Air pressure at 100 m above sea level
101 325	1.01	0.01	Air pressure at sea level (1 atm)
101 000	1.01	0.01	Overpressure of a fan
150 000	1.5	0.5	Overpressure of a

			blower
200 000	2	1	Overpressure of a rotary blower (Roots blower)
250 000	2.5	1.5	Overpressure of a screw blower
500 000	5	4	Boundary between low pressure and normal pressure
730 000	7.3	6.3	Standard pressure for compressed air tools (at full load)
1 700 000	17	16	Usual maximum permissible pressure for components
3 700 000	37	36	Ready-blown printing production of PET bottles
30 100 000	301	300	Breathing air bottles, scuba tanks
200 100 000	2001	2000	High pressure applications in the process technology

The delivery quantity refers to the volume of air sucks in by the compressor. The quantities l/s (liters per second), l/min (liters per minute) and m^3/min (cubic meters per minute) and m^3/h (cubic meters per hour) are used. In the compressed air industry, all 4 units can be used. There is no uniform name of the unit. For the performance measurement of air compressors, the conditions of ISO 1217 apply: an ambient pressure of 1 bar, a temperature (air and cooling water) of 20° C and a relative humidity of 0%. The power specification of the compressor refers to the nominal electrical power of the driving motor. The performance of the compressed air is related to an ideal isothermal compression:

$$P = \dot{V}_1 \, p_1 \ln (p_2/p_1)$$

Example: For a delivery volume V_1 = 0,1 m^3/s, an ambient pressure p_1 = 100 kPa (1 bar) and an outlet pressure of p_2 = 900 kPa (9 bar, 8 bar overpressure), the compressed air has a pneumatic power of P = 22 kW. If the driving motor of the compressor consumes 37 kW of electric power, the efficiency of the compressor is 59% (22 kW / 37 kW = 0.59).

Angesaugte Luftmenge V_n				Kompressorleistung
l/s	l/min	m³/min	m³/h	kW
1	60	0,06	3,6	0,4
2	120	0,12	7,2	0,7
5	300	0,3	18	1,7
10	600	0,6	36	3,5
20	1200	1,2	72	7
50	3000	3	180	17
100	6000	6	360	35
200	12000	12	720	70
500	30000	30	1800	175
1000	60000	60	3600	350

Table 2 Air volume in the 4-standard units, compressor capacity for 7 bar overpressure and 60% efficiency (based on isothermal compression)

Alternative Systems: Hydraulics, Direct Servo Drive, Linear Motor

Air Motors and Air Cylinders are much cheaper than more energy efficient alternatives. They are often lighter, more robust (dirt, moisture), safer (electric shock, oil leak, explosion protection) and they are cooled by the expanding compressed air. For pneumatic drives with many operating hours, direct electrically operated drives are a much more favorable alternative over the service life due to their significantly better efficiency (Table 3).

Anwendung	Maximale Wirkungsgrade*		
	Druckluft	Hydraulik	Elektro**
Hochtourige Spindel (ca. 20 000 U/min)	40 %	–	80 %
Handwerkzeug (ca. 2000 U/min)	15 %	40 %	80 %
Rührwerk (ca. 200 U/min)	10 %	50 %	80 %
Hubzylinder einfach wirkend	40 %	–	80 %
Hubzylinder doppelt wirkend	30 %	50 %	80 %
Rüttler	20 %	40 %	70 %
Vakuumbereitstellung	5 %	–	40 %
*) Gesamtwirkungsgrad (abgegebene mechanische Leistung, bezogen auf die elektrische Eingangsleistung) **) Servo- oder Linearmotor			

Table 3 Maximum possible efficiency of applications

2.2 Where do losses occur in the compressor?

During compression, the air heats up. Further heat losses occur in the compressor by the drive motor and by friction in the compressor. A large part of this heat is available as reusable waste heat up to 80°C (waste heat utilization). Another part of the energy is lost through internal leakage losses, which increase proportionally with increasing pressure. A good air compressor has an efficiency of 60%. In an air compressor, the intake air is compressed by the mechanical work done by the motor. The energy content (enthalpy) of the air increases due to the compression caused heating of the air. The hot air in the compressor is cooled down again to the ambient temperature, so that the energy content of the air (product of volume and pressure) is again the same as when it enters. The waste heat generated in the compressor thus corresponds to the absorbed electrical power, of which about 70% - 80% incurred at a usable temperature level of 60° C to 80° C. The compressed air energy is described by the physical term-exergy. The exergy corresponds to the compressor work in the isothermal compression. During expansion, the air cools down.

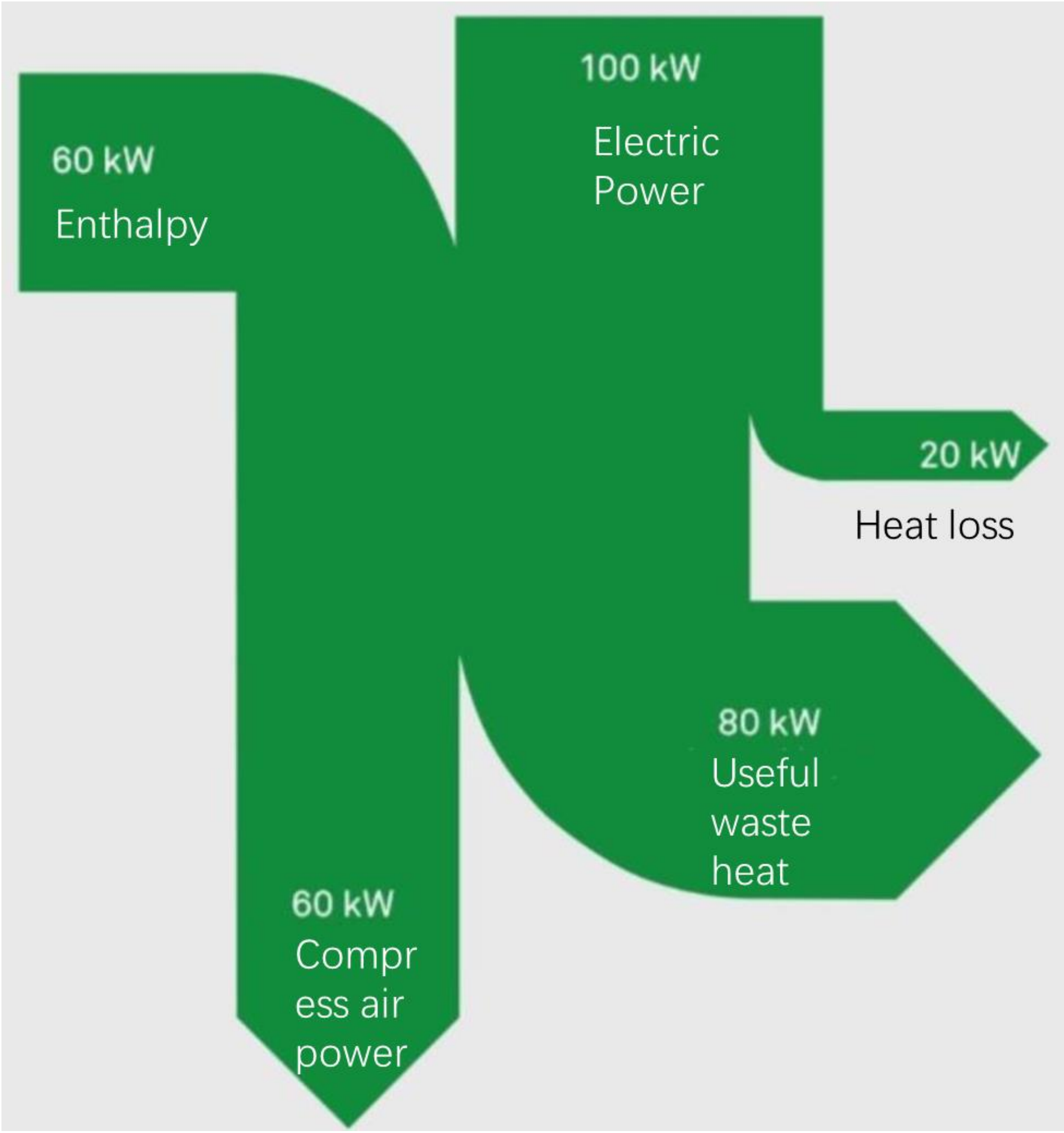

Figure 3 Energy flow Compressed air compressor. (Source: Rolf Gloor)

3.3 Where do losses occur in the compressed air system?

Depending on the system, the loss of the various compressed air components is distributed differently. A typical breakdown is shown in Figure 5.

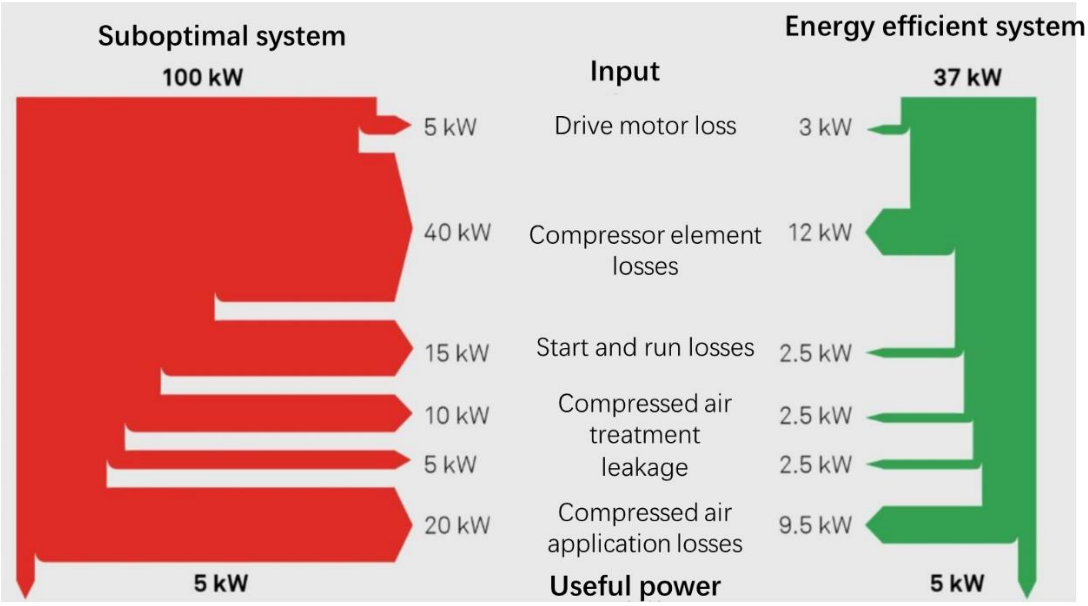

Figure 4 Air compressor system energy break-down and losses

Based on a required power of 5 kW from a compressed air system, the two examples according to Table 4 are compared: sub-optimal system (red, left) and energy-efficient system (green, right). (Source: Rolf Gloor)

Table 4 Two system energy analysis

Used power	▪ Mechanical shaft power for agitators, tools, etc. ▪ Lifting work of pneumatic cylinders for machines and valves ▪ Blowing work for cleaning filters, parts and equipment	
system part	sub-optimal system	Energy efficient system
Compressed air application (here without the possibilities of substitution by electrically operated components)	▪ Compressed air motors with 20% efficiency ▪ Double acting compressed air cylinders (also resettable with compressed air) ▪ Long bow off pulses ▪ Fixed interval for blow off pulses ▪ Large orifice blower nozzle	▪ Compressed air motors with 33% efficiency ▪ Single-acting air cylinders (spring return) ▪ Short blow-off pulses ▪ Blow-off pulses after exceeding differential pressure ▪ Injector nozzles
Leakage loss	▪ Leaking fittings and couplings ▪ Unused manual valves on the machines ▪ Condensate drain valves with fixed interval or	▪ Dense fittings and couplings (regular check with leak detector) ▪ Automatic main valves on machines ▪ Electronic condensate

	glued floats	drain valves with level measurement
Compressed air treatment	▪ Too small filters, insufficient maintenance (replacement for problems in the network) ▪ Adsorption dryer with fixed interval for regeneration (air loss 20% - 30%)	▪ For the required compressed air quality, sufficient number and size of filters, regular maintenance ▪ Refrigeration dryers and for laboratory small adsorption dryers with humidity control
Start and follow-up losses	▪ Operation of two 70 kW compressors and 300 liters of storage (short running times) ▪ Pressure range 7 bar to 8 bar	▪ Operation with two 25 kW compressors (one with VFD) and 6000-liter storage ▪ Pressure range 6.5 bar to 7 bar ▪ Higher level control
Air Compressor	▪ Inefficient compressors with 50% efficiency (isothermal) ▪ No maintenance (suction filter, etc.), warm and dusty compressor room ▪ Waste heat is dissipated insufficiently (heat accumulation)	▪ Efficient compressors with 60% efficiency (isothermal) ▪ Annual maintenance ▪ Cool and clean compressor room ▪ Waste heat recovery for domestic hot water
Driving motor	Inefficient motors with belt transmission	IE3 or IE4 direct drive, possibly with frequency converter

Energy efficiency

An energy-efficient compressed air system has a low network pressure (5 bar overpressure). Applications that require a lot of compressed air for a few hundred hours a year should, if possible, be replaced by energy-efficient alternatives (electric servo drives, linear motors, hydraulic systems, etc.). Machines or strands with hardly avoidable leaks should be disconnected from the main network when they are not in use with an automatic valve. Ideally, the compressor system will run in optimum operating range for most of the time, and energy consumption will be monitored continuously.

3.4 Efficient compression systems

The efficient compressor does not exist. It is important to consider the entire compressed air system including the treatment of the compressed air and a possible re-use of waste heat. The manufacturers of compressors are constantly working to increase the efficiency of their products in order to compete in the market. However, **an efficient compressor does not yet automatically provide an efficient compressed air system**. In addition, the compressed air consumption changes constantly over the weekly average. Simulations of a measured consumption profile can help to determine an efficient variant. Manufacturers of compressors offer brochures with basic knowledge in the field of compressed air technology, in which the individual types of compressor and processing are explained. This guideline deals only briefly with the basis of the individual components and is dedicated mostly to system optimization in more detail.

3.5 Compression principles

A displacement compressor (e.g. piston compressor) encloses a volume of air and increases the pressure to reduce this volume. Displacement compressors are the most common in the industry. In the case of a dynamic compressor (e.g. turbo compressor), the air is greatly accelerated by an impeller (turbine). The kinetic energy of the air is then converted into pressure energy by slowing down the air and compressing it. Up to now, dynamic compressors have only been built for large amounts of compressed air with output power above 400 kW. Some manufacturers are now trying to bring smaller compressors with a power below 100 kW on the market as the maintenance costs are lower than displacement compressors, but intake conditions in the compressed air system have a greater impact on energy efficiency.

Reciprocating Compressor

The reciprocating compressor is the oldest type of compressor used most frequently for smaller applications (commercial enterprises). It is single-acting or double-acting, oil-lubricated or oil-free and available in different arrangements with different numbers of cylinders (see Figure 6). With the exception of very small compressors with vertical cylinders, the V arrangement of reciprocating compressors is the most common type. Piston compressors are also available for industrial applications. In addition, they are particularly suitable for the compression of high pressures> 20 bar and special gases.

Table 5 Air compressor types

compressor type	Pressure range [bar]	Power consumption [kW]	Efficiency [isothermal]	Remarks
Piston compressor 2-stage	4-500	0.1-30	60%	No continuous operation
Screw compressor oil-free	4-16	5-500	50%	

screw compressor	4-18	5-500	60%	
Turbo compressor	3-8	30-1000	80%	
Scroll compressor	4-8	1-5	50%	
Axial fans	0.3-1.5	10-1000	70%	
Rotary pistons (Roots)	0.1-1	0.1-1000	60%	
fan	0.1-0.2	0.1-1000	80%	

Compressor comparison.

Screw compressor

The principle of a rotary positive displacement compressor with a piston in helical form was already developed in the thirties. At that time, compressors with a large and as constant as possible volume flow were required in a wide range of operating conditions. The main components of a screw element are the main and the slave rotor. These enclose a volume together with the housing, reduce it by the rotation, thus compressing the air contained there and then pushing this air out. Each screw element has a pressure ratio determined by its construction, which depends on its length, the pitch of the screw and the position and shape of the outlet. In order to achieve a very good efficiency, the pressure ratio must be adapted to the operating pressure. A screw compressor has no valves and has no unbalanced mass forces.

Liquid Cooled Screw Compressors

A liquid cooled screw compressor is cooled and simultaneously lubricated by the fluid injected into the compression chamber and bearings. In addition to the cooling and lubricating effect, the liquid additionally reduces the backflow losses in the element. In addition to lubricating oils, tests are also carried out with other liquids, such as water. Liquid cooled screw compressors are designed for high pressures. This is also the reason why a single compression stage is sufficient to produce pressures up to 15 bar. The relatively low backflow losses mean that even small screw compressors can work economically.

Dry-running screw compressors

Dry-running screw compressors (often called oil-free screw compressors) always require a synchronous transmission to drive the secondary rotor (Figure 8). Since the rotors neither touch each other nor come into contact with the housing, no lubricant in the compression chamber is required. For this reason, the compressed air is completely oil-free. The rotors and the housing are manufactured with the highest precision to avoid leakage from the pressure side to the suction side as much as possible. The built-in pressure ratio is limited by the resulting temperature difference between the inlet and outlet side. For this reason, oil-free compressing screw compressors usually have several compression stages. In addition to the designs mentioned, the scroll, speed and turbo-compressors are also available. Since only a small share of such compressors is in operation, it will not be discussed in detail here.

Air treatment (cooling, filtering, drying, etc.)

Without treatment, no defined compressed air quality is achieved, because the compressor acts like a big vacuum cleaner. The contaminants in the ambient air are sucked in by the compressor and discharged into the compressed air network in concentrated form, regardless of whether it is an oil-cooled or dry-running machine. Compressed air can rarely be used directly after the compressor without further treatment. The proportion of particles, moisture and oil in the accumulating quantities are usually too high for consuming equipment. The failure of a treatment component thus always has a negative impact on the functionality and life of the consumer devices. How pure the compressed air must be is determined primarily by the consuming side. In large compressed air systems, there are different individual consumers. One user may require a higher compressed air quality than the rest in the system. For example, systems with consumers (valves, cylinders) that are outdoors and can freeze in winter may require temporary compressed air with less humidity. This is individually dependent on the proportion and position of these consumers in the compressed air system.

Drying the compressed air

Atmospheric air usually contains more water vapor at higher temperatures and less at low temperatures. If this air is compressed, the water vapor concentration in air keeps increasing. A compressor with a flow rate of 200 l/s absorbs 80-liter water vapor from the air in 8 hours and then pushes it into the compressed air network (suction conditions: 20° C, 80% relative humidity). No moisture can be removed by filter, since water vapor is contained in the air as a gas and filters can only detect and remove solid or droplets. The selection of the compressed air dryer depends on the dew point of required pressure. Basically, the lower the dew point of required pressure, the higher of the acquisition and operating costs of the dryer. In principle, there are three different methods to remove moisture from the compressed air: cooling, over-compression and adsorption. Refrigeration dryers are sufficient for compressed air treatment in about 80% of all applications. Their use is recommended as it can save expensive maintenance costs on the pipeline network and on the compressed air consumers. When dealing with a pressured dew point between 3° C and 7° C, refrigeration dryers with energy-saving controls or with cold storage can save 50% to 70% energy compared to those measures with a hot air bypass system. Even when lower dew points are required, more expensive equipment can be used to efficiently dry compressed air down to -70° C. An example is the combination of refrigeration and adsorption dryer, which reduces the energy requirement by about two-thirds compared to conventional adsorption only dryers

Filtration of compressed air

The dust, coarse and fine filters remove solids, dust and aerosols from the compressed air. If the particles are larger than in the filter, they are held by the screening effectively. This usually only applies to particles larger than 100 µm. The filter efficiency can be increased by a finer and denser filter media. Particles between 10 µm and 100 µm are removed because of their inertia in the filter. As the air stream flows through the fibers, the particles contact the fibers and stick to their surface. The faster the air flows, the better this effect works. Very small particles (<0.1 µm) move randomly due to collisions with air molecules. Sooner or later they hit a fiber and stick to there. This process is supported by a low flow rate and a high number of fibers. The filter effect is composed of the quality of the operations mentioned. Basically, each filter is a compromise, because no single filter can achieve the same efficiency for all particle sizes. Especially the different influence of the air flow velocity prevents the same high efficiency for all particle sizes. In practice, it finds out that particles with a diameter of 0.3 microns are the most difficult particles to remove. The efficiency of a filter is always given for a specific particle size. Filter efficiency of more than 95% is achieved, which means that 5% of the particles still pass through the filter. In addition, if a filter has a higher efficiency than 95% for a particle size of 10 microns, it can still pass particles with a diameter of 30 microns to 100 microns. Oil and water droplets behave similar like solid particles and are seized by the filters. These drops gather in the filter media, flow down and drip onto the bottom of the filter housing. However, if water or oil is formed in vapor in the air, these vapors will pass through the filter. To separate oil vapors, special filter media (e.g. activated carbon), are needed. Each filter generates a pressure loss. This pressure loss is an additional energy loss in the compressed air. Very fine filters with dense filter media cause higher pressure loss, which leads to shorter service lives and higher operating costs. Efficient compressed air treatment means: no purer than required by the application process. Each treatment component generates a pressure drop and thus contributes to a poorer energy efficiency. In addition, the investment and maintenance costs will increase. It should be noted that the filter is designed large enough to have a useful life, but not be oversized, otherwise the filter performance under 20% utilization decreases sharply. Usually, a differential pressure meter is mounted on the filter housing, with which an upcoming maintenance can be detected. The activated charcoal filter with dense activated carbon or the activated charcoal absorber with loose activated carbon remove the oil vapor content from the compressed air when the air quality requirements are high.

3. Design of the compressed air system for new plants

Holistic consideration: When compressed air is targeted as a whole system, a sustainable compressed air efficiency improvement is achieved.

Correctly discuss needs

There is no universal concept for a "proper" compressed air supply, and each compressed air system should be optimized to meet individual and environmental requirements. For this purpose, the following points must be clarified in advance in order to build the basis for the design of a new compressed air system.

Network pressure plan

With the objective of operating the system with lowest possible pressure, the demand pressure of all air consumers must be checked. If, for example, a high pressure is only needed for a small proportion of the total compressed air requirement, alternative solutions must be take into consideration in order to achieve the lowest possible network pressure.

Demand volume

Optimally, a system measurement is conducted for at least one week including a weekend, to document the typical demand profile for compressed air from the consumers. This measurement can be used to record demand during the working shift, at night and weekends. If the prerequisite for a measurement of an existing system is not met, it is important to list the consumers and take into account the utilization.

Defining compressed air quality

Quality sufficiency is the main principle here, because compressed air preparation costs high! The use of compressed air is becoming ever more diverse and wide. The compressed air quality depends on the application in which the compressed air is used. A compressed air tool on a workbench does not need the high compressed air quality, such as a packaging process in the food industry. Depending on requirements, the quality of compressed air for solids, water and oil is to be defined in accordance with ISO 8573-1 (2010) (Figure 11).

The treatment of the air can be done centrally, de-centrally or combined. With a central processing but an old and polluted downstream compressed air pipes, high quality cannot be guaranteed. In these cases, a central water separation and a decentralized filtration is necessary

Oil-lubricated or dry-running compressors

The type of compressor system results from the required network pressure and the required air volume flow. On the other hand, the selection between oil-cooled or dry-running compressor is a management decision, because the same compressed air quality can be achieved by both types. Especially in industries with high quality and safety requirements (food, etc.), it is often a fundamental decision not to use oil throughout the process chain.

Redundancy

In most compressed air applications, power shortage is always associated with high costs, which is why compressed air generation is often redundant. This also applies to the compressed air production, which must ensure the quality without interruption in the event of a malfunction or service.

Future Designing

A system precisely for today's needs is not the right choice in the long term. A plant must be flexible that it can meet changing conditions and demands. Therefore, it is important to consider how the future developing tends in order to take this into consideration in the planning of a new plant.

Space

According to experience, space in plant is expensive and therefore only available to a limited extent. It is necessary to check and define different possible factors. In particular, it is important to note the location in the whole system (pressure loss), supply, air or water cooling and the possibility of using waste heat.

Cooling system

Air-cooled systems are the most cost-effective. However, if systems are installed in basement, where large supply and exhaust air installations are not possible. And the space or the size of the machine do not allow air cooling, the water cooling has its advantage in this situation.

Heat recovery

As almost all the absorbed electrical energy can be recovered in the form of heat, the recycle of waste heat must always be considered and checked. Especially for systems with high air capacity, the heart recovery investment can be quickly paid back.

Compressed air generation

For fluid-cooled or dry-running compressed air generation, screw compressors with a fixed delivery quantity (star-delta circuit) or variable delivery quantity (frequency-controlled) are mainstream. All the conditions mentioned above must be considered for the system planning. Depending on specific case, one, two or more compressors can be integrated into the solution. The following points should be noted for an efficient compressed air generation:

Delivery quantity

The delivery quantity is the quantity of air delivered by a compressor into the connected compressed air network. It is calculated back to the intake condition of the compressor. The measurement is documented for the comparability of different manufacturers in the standard ISO 1217, Annex C.

Specific power

The ratio between the supplied electric power and the amount of air discharged at the corresponding operating pressure is called specific power (Figure 12).

P_{spez} =electrical input power/delivery quantity

Selection of efficient driving motors

Depending on the required rotating speed of the compressor, asynchronous motors with different numbers of poles can be used.

Nominal synchronous speed (revolutions per minute):

- 2 poles at 3,000 rpm
- 4 poles at 1,500 rpm
- 6 poles at 1,000 rpm

- 8 poles at 750 rpm

The efficiency classifications of 0.12 kW to 1 000 kW motors are based on IEC 60034-30-1 (Figure 13). At low power range up to 10 kW, the efficiency gains of IE4 motors are very high in percentage terms compared to IE1. For larger outputs from 100 kW to 1000 kW, the percentage improvements are small, but the reduction in losses in kW is very significant. The highest efficiencies of motor can be achieved with electronically commutated permanent magnet or reluctance motors.

Illustration

Figure 5 Design of a screw compressor - determination of the specific power. (Source: Kaeser Kompressoren)

Frequency converter

The application of frequency converters (VFD) is now considered a universal solution for energy-efficient systems, but this is not always true, as 3% to 5% of the total power consumption will be caused by the application of VFD by taking into account the losses of the VFD and its effect on the motor efficiency. The use of an VFD compressor is useful in the following situations:

- strong consumption fluctuations
- low network volume
- long idle time

Frequently fixed machines for base load and VFD compressors for range control can be combined in system.

Compressor control

In addition to the compressor control, the controller should detect faults and can display them, as well as the maintenance information. Depending on how the compressor is used, a modern controller has various selectable control modes that can be chosen as needed. The connection to an upper management system or to a control system is also an option. Smaller systems often have limited possibilities of connection and management for price reasons.

Discharge condensate

The condensate is removed from the system under pressure by intelligent level control valves. In contrast to old mechanical and fault-prone arresters with floats, disturbances caused by soiling or mechanical wear are excluded nowadays. In addition, precisely calculated and adjusted valve opening times reduce the compressed air losses. Other advantages include automatic self-monitoring and possible signal transmission to a central control system.

Distribution network and accumulator tank

- Correct dimensioning of the network (diameter)
- Laying piping energy-saving
- Use suitable piping material
- Use suitable joining technique (welded, flanged, etc.)
- Design of the compressed air accumulator tank depending on network, compressor and other requirements. Rule of thumb: 1/3 of the peak load of the compressor (without VFD), example: compressor 6 m3 / h ⩾ 2 m3 compressed air tank)
- Possibly use of additional compressed air reservoirs for large compressed air consumers to bridge demand peaks.

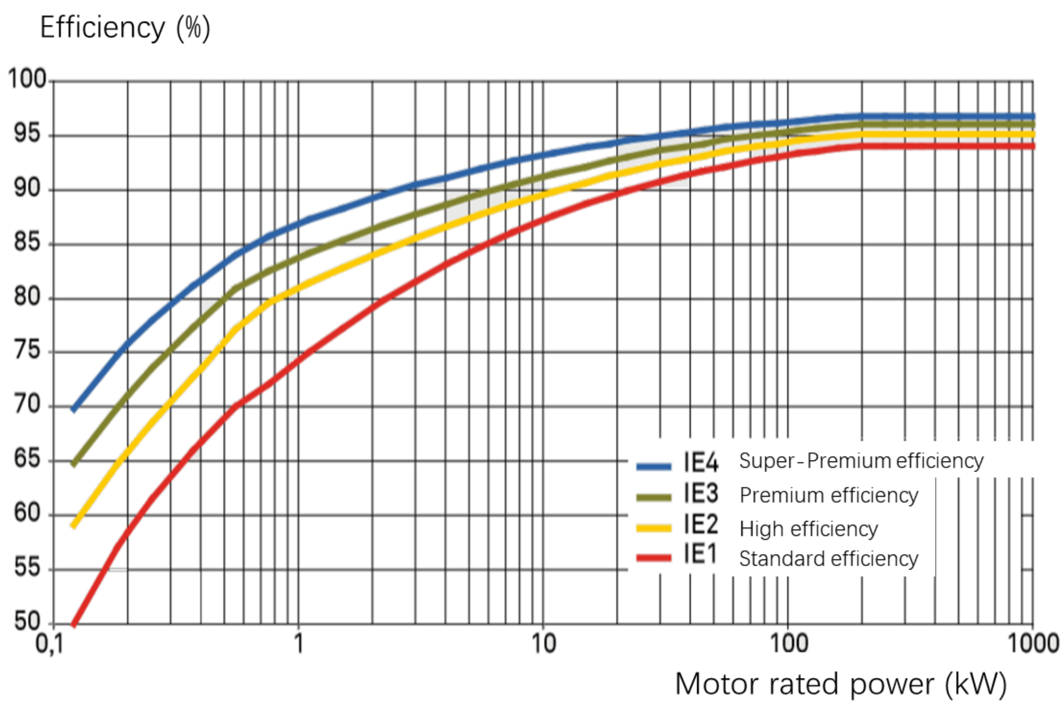

Figure 6 Efficiency as a function of the motor power of 4-pole electric motors of the efficiency classes according to IEC 60034-30-1.

Higher level control

Coordinating operation of compressors is a challenging task. Not only cross-machine controllers must be able to coordinate compressors of various types and sizes at the right time, but also they must maintain the equipment's maintenance, adjust the operating times of the compressors, and detect malfunctions to reduce the service costs of a compressed air station and increase operational safety (Figure 14)

- Efficient operation of a compressed air supply with more than one compressor
- Control and regulation of the compressor station
- Monitoring (fault)
- Total efficiency of compressed air generation (permanent monitoring)
- Data storage (demand recording)
- Connection to control system
- Energy management ISO 50001
- Central element for Industry 4.0

Figure 14 shows 4 different control methods. Several compressors are controlled by the higher-level controller so that the required pressure (range) is always available. Depending on current air consumption, one or more compressors can be activated to meet the respective requirements. The "regulation with demand pressure" offers the current optimum regulatory. In this situation, no minimum or maximum pressure limits are specified, but only the lowest possible operating pressure, which must not be allowed to fall below. The higher-level control, which takes into account all possible losses (caused by pressure increase, start-up, reaction and idle times), determine the possible optimum strategy of switching and selecting the compressors. Due to the understanding of the individual reaction times, the controller is able to prevent the failure of falling below minimum possible demand pressure and minimize pressure fluctuations in the network. In addition, the controller makes it easy to set the desired network pressure. Thus, (if possible) the network pressure can be reduced without much effort and the energy consumption may be even further cut.

Using waste heat

Space heating

The most economical way of recovering heat is to use the heat of the compressed air for space heating. This requires an air-cooled compressor through which the cooling air is introduced and heated. This type of heat recovery is economic because all heat, including the radiated heat in the compressor, is fully recovered. The heated cooling air must be transported via a duct system to the consuming space. It should be noted that the shortest possible air network should be built, because first, long path mean pressure losses in the pipes, which in turn can only be compensated by an additional fan and second, heat losses occur in the pipes with a long residence time of the cooling air. Of course, it should be noted that only the winter months can be used for the of heat recovery through space heating. In summer, the waste heat is discharged to the outside space.

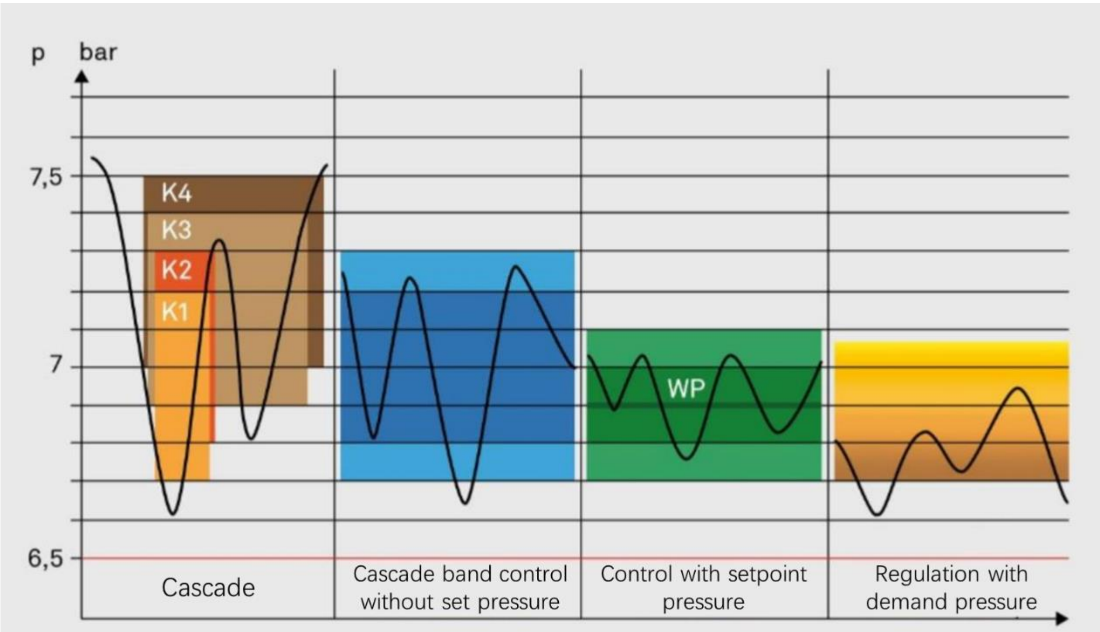

Figure 7 Various variants of superordinate compressor controls. (Source: Kaeser Kompressoren)

Heating water heating

In oil-injected rotary screw compressors, the oil carries about 70% - 80% of the supplied electrical energy in the form of heat. This energy can be recovered. It does not matter whether the screw compressor is air or water cooled. For heat recovery, the oil is passed through a heat exchanger, which can heat water by 50 K up to 85°C. It should be noted that water is only heated when the compressor is operating in load mode. Since compressors are not always in load operation and thus not always warm water can be produced, the water heated by heat recovery can only serve to support the heating circuit.

Call for tenders

The basis for the preparation of a call for tenders are the conditions clarified in the sections mentioned above, includes: network pressure, delivery quantity profile, quality, redundancy, cooling system, available space and waste heat recovery. In order to make the individual offers comparable, the requirements must be clear and formulated with the necessary delimitations. In addition to the technical conditions, a brief general report is helpful in describing what the purpose of the project is and what the compressed air is used for. Together with the general terms of delivery, the documents can then be handed over to the contractors. A more detailed version of the call for tenders, such as number of compressors, rated power, number of machines with frequency converter or even a completed scheme of compressed air supply is usually not necessary. On the contrary, it restricts the companies to be able to offer a holistically considered energy-efficient plan. It is therefore more important to define clear acceptance conditions. This can be, for example, a performance measurement in the factory, a quality measurement on-site during commissioning of the plant or even a permanent monitoring of the dew point with alarm output. Without a prior agreement, subsequent qualified measurements according to regulations can only be realized with greater effort and should therefore be clarified with the manufacturer before ordering. Figure XXX shows the cost distribution of an optimized system with air-cooled compressed air station (running time: 5 years, electricity price: 8 cents/kWh (USD), interest rate: 6%, 7 bar working pressure, compressed air quality according to ISO 8573-1: residual oil class 1, residual dust class 1, residual water class 4). The example shows that even under optimal conditions, energy consumption accounts for around 70%t of total costs. It is therefore financially worthwhile to invest in energy-efficient systems. This should be taken into account when evaluating different offers, otherwise there is a risk that the manufacturer will offer solutions that are not optimally tailored to the actual needs.

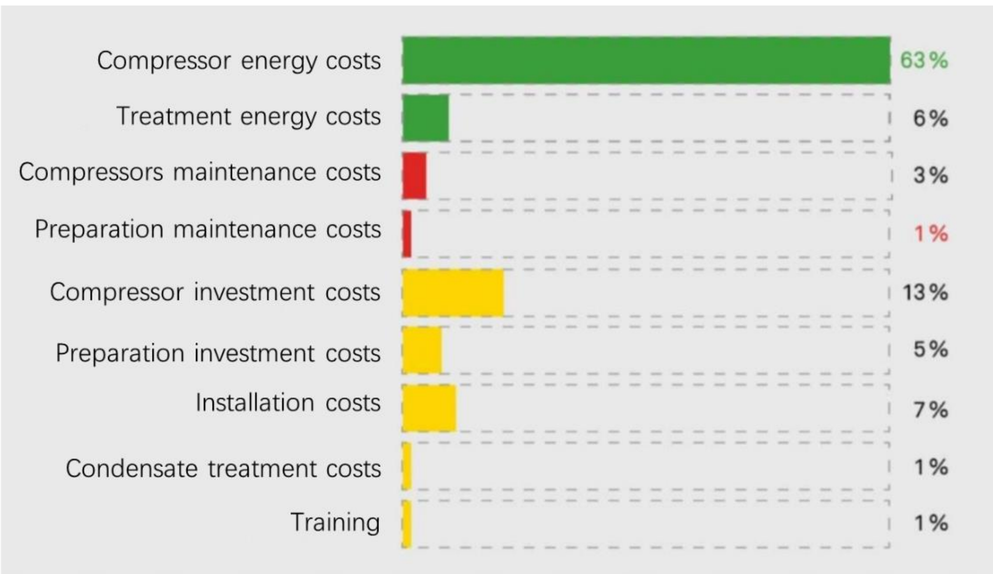

Figure 8 Cost structure of an optimized compressed air system. (Source: Kaeser Kompressoren)

4. Optimization of existing compressed air systems

Observations and measurements on site

The following data should be measured for a meaningful analysis:

- Load/Idle, power consumption of the compressors. As a result, a load profile can be produced, which shows the interaction and the operating states of the compressors. It shows the load and idle ratio and, for frequency-controlled compressors, the operating time in the optimal control range. If financially and installation-related possible, the flow rate can be measured to each compressor, which allows an understanding about the efficiency of the compressors.
- Network pressure before and after compressed air generation and at critical points in the compressed air network. This shows whether the dimensioning of the system components is correct and whether the settings are correct.
- The flow volume at the outlet of the compressed air system shows how much compressed air is needed by the process. Ideally, individual partial strands are also measured (e.g. in different halls), so it is possible to make an understanding how much compressed air is consumed and where to optimize is the easiest way to achieve savings.
- Ideally, these measuring points are immediately installed as permanent measurements. The effect of optimization measures can be proven perfectly.

The compressed air system forms a closed system, which supply a certain amount of compressed air at a desired operating pressure with defined quality. Thus, there are only a few places and interfaces for the suppliers and auditors can easily obtain the necessary information for latter the analysis and subsequent optimization. Comprehensive analyzes require the operator, together with the specialist, to analyze the entire compressed air system, including the processes, and to check possible optimization measures. In addition to the operator, production manager must also be involved in, especially in larger companies. ISO 11011 is related to ISO 50001. ISO 50001 is a standard for energy management systems (EMS). However, ISO 11011 is a new, worldwide standard for energy audits on compressed air stations. Before ISO 11011, everyone could carry out energy investigations, air tests and data logging with regard to compressed air consumption. Without a recognized standard, the discrepancies among the results were large. Now the compressed air system energy audit process has been standardized; with guidelines that not only focus on the assessment of compressed air leaks, but also include the auditor's competencies and methods. The objectives of this standard are improved measurements and the identification of potential for improvement. The focus is on the entire compressed air system, including production, distribution and demands.

Avoiding leaks

No more compressed air might be used for any process than for leakages. Leaks arise, multiply and increase in compressed air systems over years. However, even on new facilities, you will encounter leaks. Repairing leaks requires a certain tenacity. The process of leakage reduction should be firmly fixed in the daily operation. It is often difficult to reduce the leaks, as a large part of them comes from the machines with compressed air consumption.

Adapted compressor/motor power

How big should compressors be sized? If it is an existing compressed air system, the question is easy to answer: A simulation can be used to work out the most economical factors. As a rule, 2 to 4 compressors in combination with a higher-level control system work best. How to proceed in a new system? If the future compressed air consumption is difficult to assess, a flexible solution with rather small-sized compressors has proven to be suitable. Because systems are often planned with excessive security margin for production, as a result, the planned compressed air requirement is often higher than the actual consumption. In this case, if the procured compressors are higher than the planned consumption, the investment, maintenance and energy costs are higher than necessary.

Regulation as required: VFD

In the event of large fluctuations in demand, the use of one or more variable-speed compressors must be checked. Compressors equipped with a frequency converter with asynchronous motors or permanent magnet motor inverters can vary the speed of the compressors and thus the amount of generated compressed air. Thus, a variable range of compressed air between 15% and 100% can be generated. A variable speed compressor is used efficiently when it is operated at a majority between 30% and 80% of the nominal power. If the compressor runs mostly in the lower rpm range (e.g. at night and on weekends), other solutions are more efficient. If the compressor is operated in conjunction with other fixed-speed compressors, make sure that the variable-speed compressor is larger than the fixed-speed compressor to avoid gaps in the regulator.

Efficient components: motor and compressor.

If older compressors are not yet to be replaced due to their condition, it pays off to invest in a new electric motor and a new compressor, depending on performance and operating time. This measure must be well thought out, because these components do not make a new compressor yet. Old compressors have greater internal flow resistance in air intake filters, intake valves, separators, coolers, and water separators than new generation. In general, such a measure can be checked if the following criteria are met: The compressor still adapts to the current consumption profile due to the delivery quantity and the pressure level. It performs more than 4000 operating hours per year, has an output of at least 50 kW and is less than 15 years old,

5. Practical examples

Three instead of five compressors

A consumption analysis is carried out in a compressed air system and the supplier then offers new compressors with an increase in efficiency. The project will be implemented and the promised increase in efficiency will be realized. The disadvantage proved that after one of the new compressors has replaced the old one, but even a nearly 20 years old refrigerant dryer was still used. The replacement with a new dryer could have been the same with the installation of the new compressor and thus reduces the subsequent installation costs. In addition, the person responsible for the operation had to submit a new application to the management. Due to the energy savings of the new refrigeration dryer, the payback period was less than 2 years. After filter cleaning, all 5 compressors run in the compressed air system for a short time. In addition, the network pressure drops by around 1.5 bar during this time. This is repeated three times an hour. To ensure that all consumers run smoothly during the cleaning process, the network pressure is 1.5 bar higher than required. This generates an approximately 10% higher energy consumption when compressing the compressed air and an approximately 18% higher compressed air consumption for unregulated consumers.

Optimization measure: A large air tank with volume of 24 m3 is installed before the cleaning process. The inlet to the tank is reduced in cross section, so that only a small amount of compressed air can flow. However, this is sufficient to fill the container volume in the time between the cleaning processes back to the operating pressure. Optimization: Reduction of the total amount of compressed air consumed by a lower network pressure, reduction of energy for generating the compressed air, only a maximum of three instead of five compressors are needed.

Coordination through the operation

On a packaging machine, the packaging can not be cut properly if the pressure is too low. According to the manufacturer, an operating pressure of 7.0 bar is required, the required amount of compressed air during the cutting process could not be quantified. However, the entire compressed air network runs to 8.5 bar, so that the packaging can be cut cleanly. Before the packaging machine, a pressure reducing valve was installed, which seemed to be too small and was turned up to the stop. Unfortunately, there was no change in the before-after: the recommendation to remove the pressure reducing valve and install a larger pipe cross-section. The energy savings were estimated at 30 000 kWh/year and the optimization measure would have been paid in less than a year. This example is intended to show that optimizations to the compressed air system always require the will of all persons' involvement. For this reason, it is advisable that the coordination of optimization projects in the field of compressed air is under the supervision of a person in the company who can also enforce the instructions on the affected areas.