action matters for business

i am your compressed air guide

Low capital cost, simple solutions to improve the efficiency of your compressed air system

NSW GOVERNMENT Office of Environment & Heritage

In partnership with: AiGROUP

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Foreword

A rapid rise in energy costs is a major problem facing Australian industry. While sustainable solutions are emerging, their implementation relies on both the supply and demand sides making changes.

Ai Group welcomes the publication of this guide on improving the efficiency of compressed air systems. We are proud to have assisted in its production. It addresses the two barriers that most often prevent companies from reaping easy wins on the demand side through energy efficiency.

There is more information available than ever before about energy options from advisers, consultants and technology providers; however, the quality of advice varies widely. Energy technology has changed rapidly and not every adviser has kept up; it is difficult to know who to trust. It is essential to have access to the best advice compiled by an independent and credible source.

Finance is the other challenge for many. Businesses still struggle to attract or find the funds for major energy efficiency upgrades. It is important to know you haven't overlooked low capital cost options, which are the focus of this guide.

If you use compressed air in your operations, particularly multiple compressor systems, we recommend this guide for your business.

Mark Goodsell
Head – NSW
National Manufacturing Lead
Australian Industry Group (Ai Group)

Contents

List of acronyms and abbreviations

barg	gauge pressure in bar
CSF	compressor system factor
DC	duty cycle
DCV	directional control valve
ESC	energy saving certificate (NSW Energy Savings Scheme)
FIFO	first in, first out logic
FILO	first in, last out logic
kPa	kilopascal
kPag	gauge pressure in kPa
kW	kilowatt
kWh	kilowatt-hour
M&V	measurement and verification
OEH	Office of Environment and Heritage (NSW)
P_L	compressor load pressure
POU	point of use
P_U	compressor unload pressure
PLC	programmable logic controllers
Q_{AV}	compressor's average flow, in m^3/min
Q_R	rated compressor flow, in m^3/min
SCADA	supervisory control and data acquisition
T_L	time a compressor is loaded in seconds (includes delivering air and pump-up times)
T_U	time a compressor is unloaded in seconds (including blow-down time)
V_{EFF}	effective volume: includes both the wet and dry sides of the system
VCC	variable capacity compressor
V_{ST}	Volume stored by the system per cycle at 1bar

Photo: Wat Als Photography/OEH

About this guide

This compressed air guide is for operators of compressed air systems, maintenance staff, production managers and other technical staff who wish to optimise the efficiency of their compressed air systems without spending significant capital. This guide sets out **low capital cost, simple-to-do** actions that can help you to:

- free up system capacity to better meet your air demands
- save money by avoiding or delaying buying a new compressor
- complement your efforts to ensure system reliability
- reduce your electricity bills.

By implementing all of the actions in this guide on a system that has not been optimised, you could save up to 50% of the energy used by your compressed air system.

The high cost of energy

Over the 10-year life of an average compressor system, energy is the largest cost component. When combined with ongoing maintenance costs, it's estimated that energy makes up to 85% of the total cost of compressed air.

Figure 1: Average compressor costs over 10 years

Running your compressed air system efficiently is the key to reducing these costs. In addition, an efficient system can go hand-in-hand with operation and maintenance efforts that target system reliability.

What's covered in this guide?

This guide has two main parts:

Part 1: Implement low capital cost, simple-to-do actions

Part 1 of the guide sets out 15 energy efficiency actions that can deliver large savings across your compressed air system. These actions start in the compressor house before targeting wasted air downstream.

Unlike many other guides, which focus on demand-side actions first, starting by finding efficiency opportunities in the compressor house will also benefit the demand side by reducing waste, including from air leaks. This approach will give you a better return on your time and money as well as enhancing your production operations by providing stable, clean and correctly pressurised air.

Part 2: Review your system and estimate potential savings

Part 2 of the guide builds on the principles of compressor system efficiency and the interactions between your compressor and the system. This helps you understand compressor part-load efficiencies. By the end of this section you will be able to:

- get a snapshot of your system's efficiency and performance
- quantify your potential savings opportunities.

This analysis is illustrated using several worked examples and then expanded in the appendices.

Where do you start?

You may prefer to get going with the simple-to-do actions presented in Part 1 of the guide, or you may prefer to start by reviewing your compressed air system – following the advice presented in Part 2. This is a more strategic approach and will help you to prioritise your actions according to your system and available resources.

Either way, you will find opportunities to improve your system and save on energy costs.

Part 1: Implement low capital cost, simple-to-do actions

Photo: Wat Als Photography/OEH

Figure 2 on the following page illustrates the 15 energy-saving actions presented in the first part of this guide. The indicative savings given here include both the compressor power savings (direct savings) and, where applicable, savings realised downstream as a result of the actions (indirect savings). Savings for actuators and vacuum systems are provided as a percentage of the device's air demand.

Maintain your system

Action	System savings	Page
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5 Maintain your line filters	2–15%	22
6 Service and upgrade your drains	Up to 20%	23

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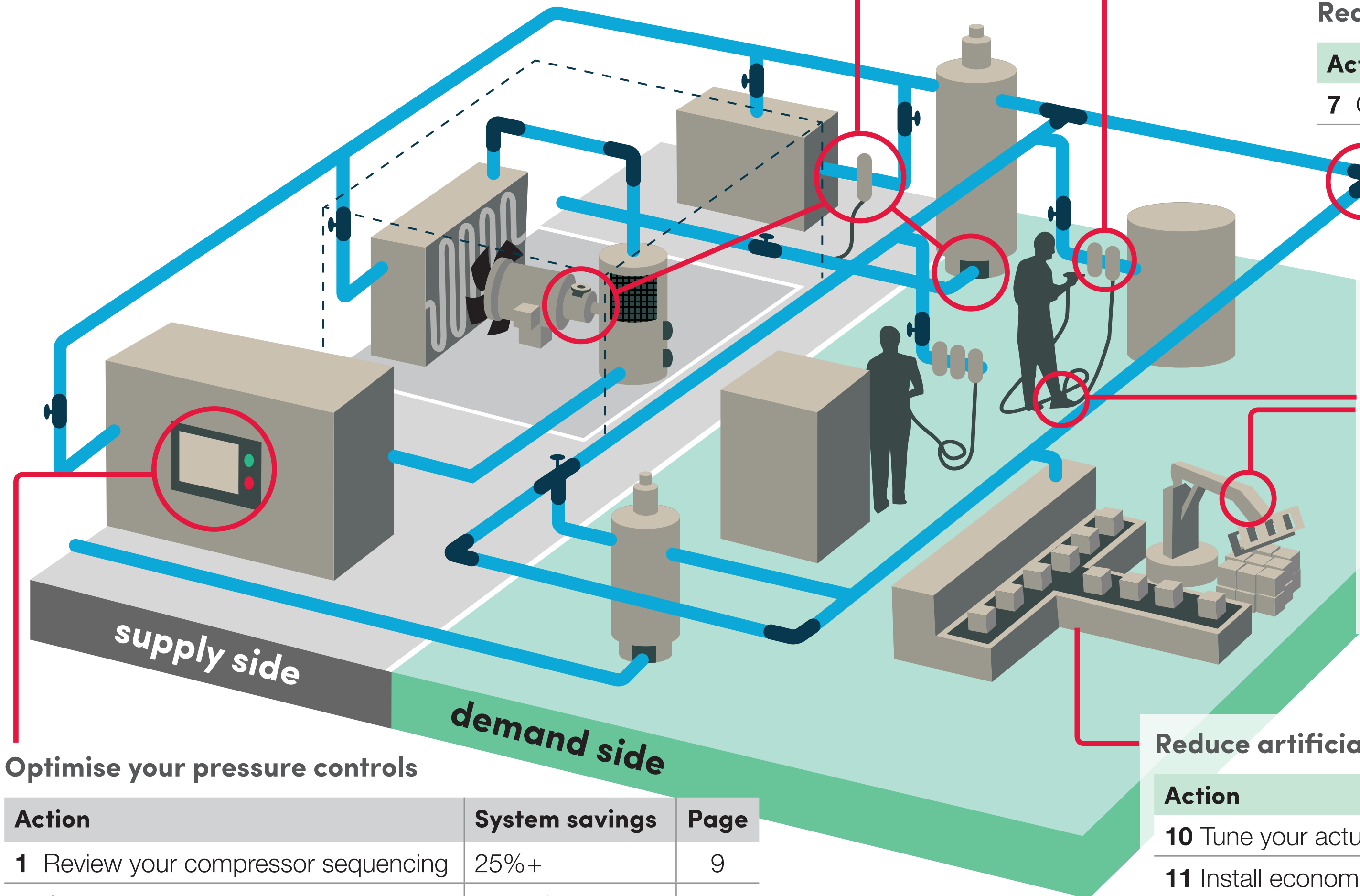
Action	System savings	Page
8 Check your regulator settings	5–30%	29
9 Reduce pressure drop at your regulators	5–15%	30

Reduce leaks

Action	System savings	Page
7 Check and fix air leaks	Up to 30%	26



Reduce inappropriate use and waste of compressed air

Action	Savings per device	Page
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15 Reduce wasted air in vacuum systems	More than 50%	37

Optimise your pressure controls

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Reduce artificial demand – actuators

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10 Tune your actuators	Up to 10%+	34
11 Install economiser regulators	Up to 25%	35
12 Reduce wasted volume in tubing	Up to 20%	35
13 Re-use air from actuators	Up to 90%	36

Figure 2: Energy-saving actions and their location within a typical compressed air system

Photo: Wat Als Photography/OEH

Actions to optimise supply side: compressor house operations

The first step to improve your compressed air system is to start inside the compressor house. The savings gained from optimising compressor house operations are generally more cost effective than those from the demand side. The effects will flow downstream, and the actions are typically easier to implement.

For example, by reducing the average system pressure in the compressor house, you will not only save in compressor power, but also reduce the rate of leaks downstream in your system. This can be more cost effective than if you had to achieve the same power savings by finding and fixing leaks.

Start at the compressor house

> **Saving energy is not just about fixing leaks and reducing demand for air. To reduce energy consumption, operators should first understand what's happening in the compressor house.**
>
> Murray Nottle, Working Air System Engineer, The Carnot Group

This section provides practical measures to improve the efficiency of your compressor house by optimising compressor controls, and through maintenance practices that prioritise system efficiency.

Optimise your compressor controls

As few air systems operate at full load all the time, part-load performance of your trimming compressor is critical and primarily influenced by compressor type, size and control strategy.

What is a trimming compressor?

This is the compressor that is not at full load and that is controlling your system pressure, as shown in Figure 3. Depending on how your compressors are sequenced, the trimming compressor may change with system air demands.

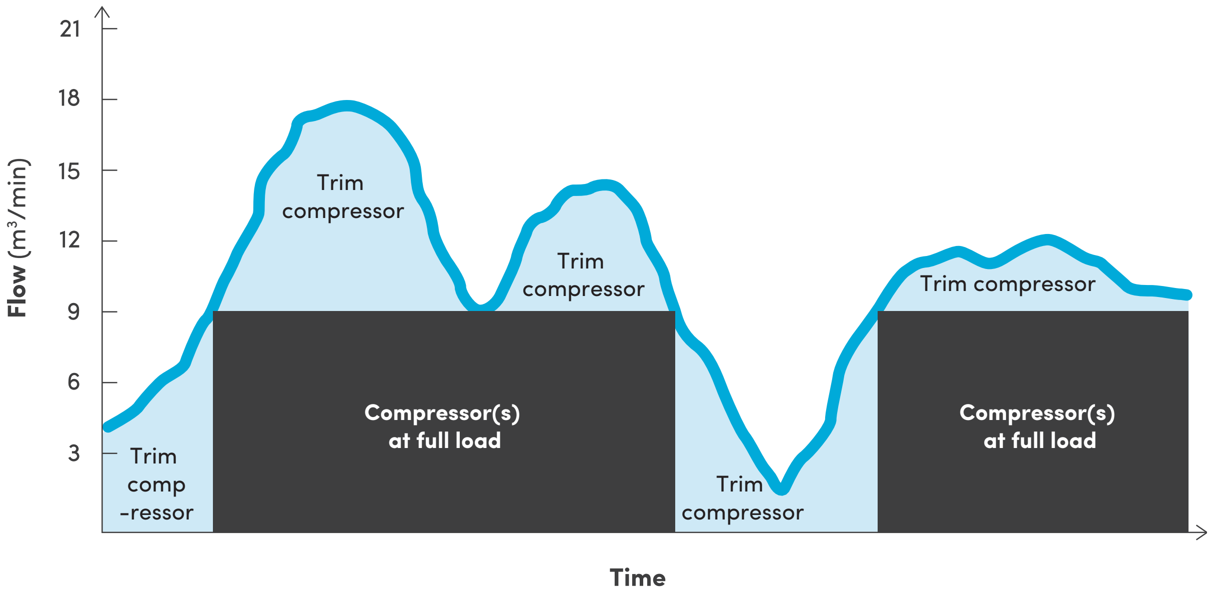

Figure 3: Schematic representation of a variable load showing the trimming and full-load compressors

A control system should meet system demand by first shutting off unneeded compressors or delaying additional compressors coming online until needed. At the same time, they should be operated at or near their maximum efficiency levels.

Action 1: Review your compressor sequencing

Set your compressor system to centred sequencing using first-in, first-out logic (FIFO)

POTENTIAL SAVINGS: 25%+

Compressor sequencing is controlling the order in which your compressors are added to (loaded) or removed (unloaded) from the system and is dictated by a sequencing action and logic. It is generally carried out either on system-wide controllers or on individual compressor controllers.

When implementing compressor sequencing consider the following key principles:

- The compressors with the best part-load efficiency should trim the system regardless of the number of compressors running.

- The order of trimming compressor selection is any variable capacity units first, followed by the smallest fixed-capacity compressor. Leave the biggest ones last.
- The compressor with the best full-load efficiency should never be the trim compressor, unless it also has the best part-load efficiency.
- For a system with a variable capacity compressor (VCC), the next compressor to load or unload should have a capacity smaller than the turn-down range of the VCC.
- If you only have fixed-speed compressors, set the load/unload pressure of your smallest compressor to the smallest band of your average system pressure. With your next largest compressor, increase the load/unload pressure band. Continue this with all of your compressors. Ensure the load pressure of your largest compressor is at or greater than the minimum system pressure.
- For small air demands, it may be more efficient to have a small fixed-capacity compressor cycling (load/unload) instead of a big variable-capacity compressor running lightly loaded.
- Make sure there is enough difference between the load pressures of the compressors, so they have enough time to start and load before the pressure reaches the load setting of the next compressor in the sequence.

Saving energy by running a smaller trim compressor

Figure 4 shows the efficiency curves of two compressors trimming the same system. The larger (black) unit is 132 kilowatts (kW) and the smaller (red) one is 75kW.

At any airflow the larger compressor uses roughly twice the power as the smaller one. This indicates that by choosing your trimming compressor wisely you can achieve substantial energy savings.

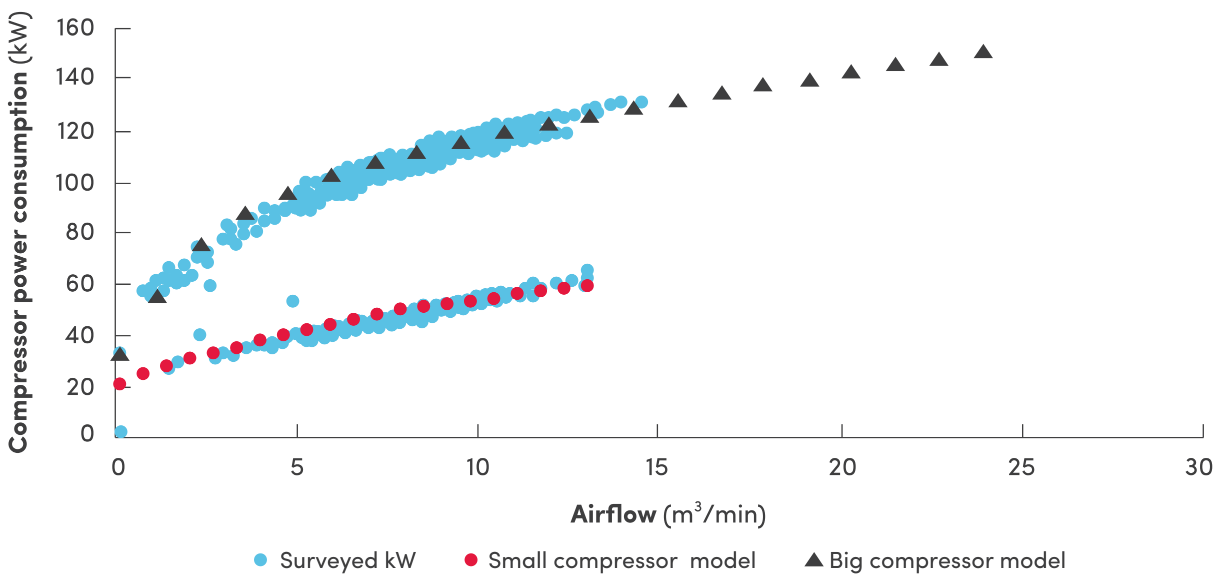

Figure 4: A comparison of the efficiency curves of two trimming compressors

The following section provides information on the various common compressor logics and actions.

Compressor sequencing logic

Compressor sequencing logic chooses which machine in what order will load and unload at any point in time.

First-in, first-out (FIFO) logic

The compressors are:

- loaded by finding the first unloaded compressor – restarting from the top of the list
- unloaded by finding the first loaded compressor – restarting from the top of the list.

This always allows the smallest compressor to trim the system – hence is the most efficient.

Loading	Status after	Unloading	Status after	Loading	Status after
1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

First in, last-out (FILO) logic

The compressors are:

- loaded by moving down the list
- unloaded by moving back up the list.

Loading	Status after	Unloading	Status after	Loading	Status after
1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Circular (CIRC) logic

The compressors are:

- loaded and unloaded by moving down the list, restarting the list once the end is reached.

This logic is usually only used with compressors that are not 100% duty rated (e.g. small piston compressors) and need to cool down between periods on load.

Loading	Status after	Unloading	Status after	Loading	Status after
1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

Advanced sequencing logic

More advanced sequencing logic will consider:

- how to control and interact with variable capacity compressors
- the relative size and full-load efficiency of any running compressors. This may swap out a compressor for one with a higher efficiency.

Compressor sequencing actions

Compressor sequencing actions, typically using pressure, trigger the loading and unloading of the compressors. There are three main actions: centred, cascade and delayed. Centred action uses the more efficient logic, FIFO. Cascade action uses FILO which is the more common but less efficient approach, and delayed action can use either FIFO or FILO, but FIFO should be preferred.

Centred sequencing – the most cost-effective approach

Centred action can be applied using the compressor load and unload pressure settings. It does not need a system controller, and so can be applied without any new capital expense. Because it is pressure-based, this action can be implemented using each compressor's pressure settings without any connection between machines.

Centred action by default uses FIFO logic.

In centred sequencing, the compressor outlet pressure is reduced and the smallest compressor is kept on trim duty. Figure 5 is a schematic of centred control using typical pressure settings. When the system pressure drops to 7.1 bar gauge (barg) or 710 kilopascals gauge (kPag), fixed speed Compressor 1 starts (loads). If the system pressure continues to drop to 7barg, then fixed speed Compressor 2 starts, and so on.

By the time the system pressure reaches 6.9barg, then all three fixed-speed compressors are loaded. As air demand decreases, and system pressure increases to 7.3barg, then fixed-speed Compressor 1 stops (unloads). When system pressure increases to 7.4barg, then fixed-speed Compressor 2 unloads. By the time the system pressure reaches 7.5barg, all three fixed-speed compressors have unloaded.

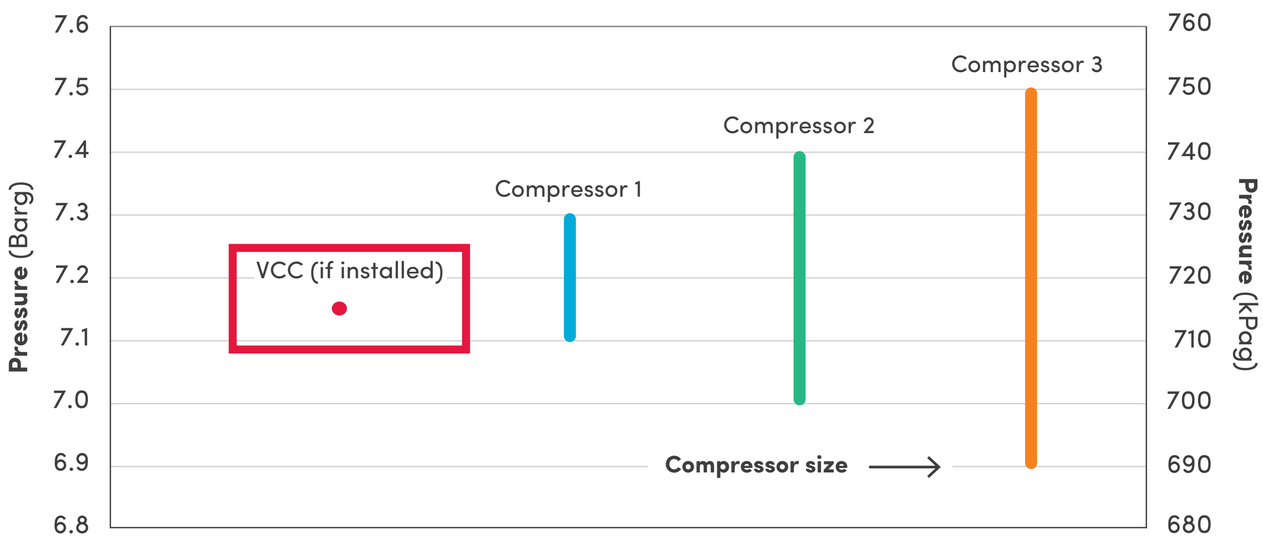

Figure 5: Schematic representation of a centred control setting for multiple fixed-speed compressor systems and a variable capacity compressor if installed

If a VCC is your trimming compressor, set its target pressure to the load pressure of Compressor 1 plus 25% of its pressure band (7.1 + 0.2 x 0.25 = 7.15barg). The range of the load and unload pressure set points should increase with compressor size.

Cascade sequencing

Cascade sequencing is a traditional approach to controlling operations of multiple single-speed compressor systems. The load/unload pressure settings are different for each compressor, while the pressure band is often identical.

Cascade sequencing by default uses FILO logic.

While it is simple to implement, cascade sequencing has a number of potential disadvantages:

- the compressor air outlet is usually at a higher pressure than required
- it does not accommodate different sizes of compressors very well
- it does not keep the smallest compressor on trim duty.

As shown in Figure 6, as the system pressure drops to 7.1barg, Compressor 1 loads. If the system pressure continues to drop to 7barg, then Compressor 2 loads, and so on. By the time the system pressure reaches 6.9barg, all three compressors are running. As air demand decreases, and system pressure increases to 7.3barg, then Compressor 3 unloads. By the time the system pressure reaches 7.5barg, all three compressors have unloaded.

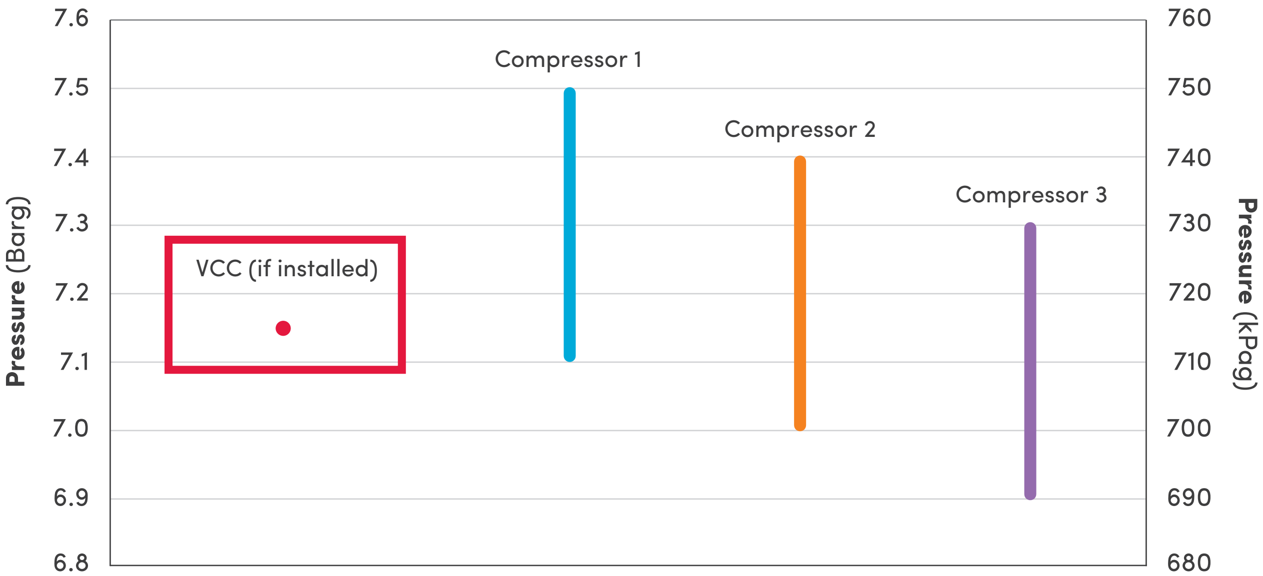

Figure 6: Schematic representation of a cascade control setting for multiple fixed-speed compressor systems and a variable capacity compressor if installed

If a VCC is your trimming compressor, its target pressure should be a value between the load pressure of Compressor 1 and the unload pressure of Compressor 3.

Delayed sequencing

Delayed sequencing allows the lowest average system pressure and the widest pressure band for each compressor. It uses a timer between the compressors to control the load/unload of subsequent compressors. The cost of such a controller can be high and is only recommended for systems with four or more compressors.

Delayed sequencing can follow different logic methods. However, it usually is FILO.

The load and unload pressures for all compressors are often identical. In Figure 7, when system pressure drops to below 6.9barg, Compressor 1 and a timer starts. At the end of the set duration, if the system pressure is still at or below 6.9barg, Compressor 2 loads, and so on. When air demand decreases and system pressure increases, depending on the control logic, the first or last compressor to load will be the next compressor to unload (turn off).

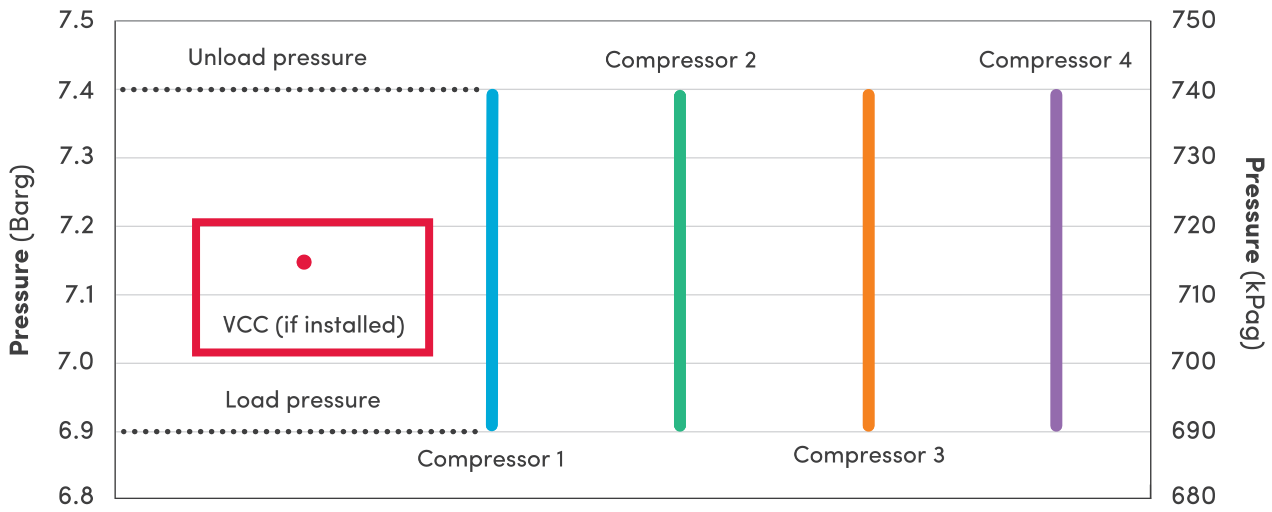

Figure 7: Schematic representation of a delayed control setting for multiple fixed-speed compressor systems and a variable capacity compressor if installed

If your trim compressor is a VCC, its target pressure should be to the average system pressure.

Action 2: Choose the optimal pressure band

Adjust system load and unload pressure settings for optimal system efficiency

POTENTIAL SAVINGS: 2%–15%

For most air systems, there is an optimal load to unload pressure that maximises the compressor system efficiency. It considers gains in trim compressor efficiency from increasing load to unload pressure band, and the subsequent losses from higher compressor power and artificial demand due to increased average system pressure.

This action involves calculating some basic system parameters and looking up a table to find your optimal pressure band.

Calculating optimal load and unload pressure settings

Step 1: Calculate the system volume relative to the trimming compressor capacity:

$$\textit{Relative volume (\% of trimming compressor capacity)} = 100 \times \frac{V_{EFF}}{Q_R \text{ trimming compressor}}$$

Where

- V_{EFF} is the effective system volume (m^3) which includes both the wet and dry sides of the system
- Q_R is rated compressor flow in m^3/minute.

NOTE: for systems with small demand-side stored volumes, you can use your wet receiver volume instead of the effective volume. For larger systems you will need to calculate it – see **Using CSF to assess your savings** on page 48.

Step 2: Calculate the ratio of the trimming compressor capacity to the total running compressor capacity:

$$\textit{Trim \% of duty} = 100 \times \frac{Q_R \textit{ trimming compressor}}{Q \textit{ total running compressor}}$$

Step 3: Estimate the leak rate % of demand:

$$\textit{Leak rate (\%)} = 100 \times \frac{\textit{estimated air leak}}{\textit{system air demand}}$$

Where:

- Estimated air leak and system air demand are in m^3/minute.

Step 4: Using the calculated values from Steps 1–3, refer to Table 1 and find the corresponding pressure band.

Table 1: Optimal pressure band for trimming compressors (pressure units: bar)

Trim % of duty →	100			50			33			25		
Leak rate % demand → / Relative volume % ↓	20	40	60	20	40	60	20	40	60	20	40	60
5	2	0.9	0.35	0	0	0	0	0	0	0	0	0
10	2.8	2	1.5	1	0.45	0.15	0	0	0	0	0	0
15	2.5	2.1	1.7	1.4	0.9	0.6	0.65	0.3	0	0.15	0	0
20	2.3	1.9	1.6	1.4	1	0.75	0.9	0.55	0.35	0.5	0.25	0.1
40	1.6	1.4	1.3	1.1	0.95	0.9	0.9	0.7	0.55	0.7	0.5	0.4
60	1.8	1.8	1.8	0.95	0.8	0.7	0.75	0.65	0.5	0.65	0.5	0.4
80				0.8	0.7	0.65	0.7	0.55	0.5	0.55	0.5	0.4
100				1.1	0.6	0.55	0.7	0.5	0.45	0.5	0.45	0.4

When choosing the optimal pressure band, consider the following:

- Some optimal load to unload pressures may be impossible due to compressor maximum and minimum pressures.
- The trimming compressor may change depending upon the compressor sequence.
- The proportion of artificial demand will vary with changing load.
- For any cells in the table with a zero value, the volume is too small for there to be an optimal load to unload pressure; choose a value to suit the trim compressor/system for a higher trim % of duty.
- For VCC, rated compressor flow (Q_R) should be adjusted as follows:
  - for the relative volume calculation in Step 1, Q_R is the rated minimum turn-down capacity of the compressor
  - for the trim % of duty value in Step 2, the full load capacity of the compressor (Q_R) should be scaled down, based on the relative power draw at minimum turn down.

    For example, a 10 m^3/min compressor modulating to 70% of full load will use 91% of full load power. Hence the trim % duty value should be 10 x 0.91 = 9.1 m^3/min.
- If your compressors trim % of duty value is smaller than 25%, you can scale it down proportionally based on the pressure band at 25%, as defined by:

$$\textit{pressure band (trim \% of duty} < 25\%) = \textit{pressure band (trim 25\% of duty)} \times \frac{\textit{trim \% of duty}}{25\%}$$

Worked example A:
Calculating optimal pressure bands for two operation modes

System details

Compressors	2 x 29 m^3/min
	1 x 23 m^3/min (trimming)
Effective system volume	19 m^3
Air leaks	approximately 20 m^3/min

Operation mode 1: one large compressor running, smaller compressor trimming and air demand at 45m^3/min

Step 1: Calculate the system volume relative to the trimming compressor capacity

$$100 \times \frac{19}{23} = 83\%$$

Step 2: Calculate capacity of the trimming to total compressor capacity running

Total running capacity is: 23 + 29 = 52 m^3/min

$$\text{Trim \% of duty is: } 100 \times \frac{23}{52} = 44\%$$

Step 3: Calculate leak rate % of demand

$$100 \times \frac{20}{45} = 44\%$$

From Table 1, by taking 80% relative volume and 40% leak rate, the optimal load to unload pressure for this compressor is between 0.7 (trim % duty is 50%) and 0.55 (trim % duty is 33%).

As 44% is roughly two-thirds between 33% and 50%, the optimal load to unload pressure value is:

$$0.55 + (0.7 - 0.55) \times \frac{2}{3} = 0.65$$

Operation mode 2: both larger compressors running, smaller compressor trimming and air demand at 70m^3/min

Step 1: Calculate the system volume relative to the trimming compressor capacity

$$100 \times \frac{19}{23} = 83\%$$

Step 2: Calculate capacity of the trimming to total compressor capacity running

$$100 \times \frac{23}{(2 \times 29 + 23)} = 28\%$$

Step 3: Calculate leak rate % of demand

$$100 \times \frac{20}{70} = 29\%$$

From Table 1, by taking 80% relative volume and 25% trim duty, the optimal load to unload pressure for this compressor is midway between 0.5 (leak rate at 20%) and 0.55bar (leak rate at 40%), so use 0.52bar.

Summary

In the above example, it is assumed the system spends more time with a demand near 45m^3/min, rather than at its peak demand (70m^3/min), hence the optimal load to unload pressure for the compressor should be set closer to 0.65bar than 0.52bar.

If your controllers allow for pressure scheduling then set the pressures to suit each operating mode: for Operation mode 1, set pressure band closest to 0.65bar and for Operation mode 2, set it closer to 0.52bar.

Implementing optimal pressure band

Once you have worked out your optimal pressure you can adjust your compressor pressure settings by:

- adjusting your compressor's load pressure as determined by the largest minimum pressure required by your processes and equipment, known as the critical point of use (POU)
- adjusting your compressor's unload pressure as determined by your optimal pressure band. Note this pressure should be within the compressor's rated capacity and that of the downstream equipment.

When choosing pressure settings, consider that on most machines the minimum increment is 0.1bar (10kPa).

Finding your critical point of use

The most direct approach to reduce system pressure is achieved by dropping the pressure a little, week by week, until production is about to be affected. At this point, the pressure at the critical point of use (POU) has been reached and the most pressure-sensitive process identified.

For an efficient system, the pressure difference between your compressor outlet and your critical POU should be no more than 10% of the discharge pressure, or 0.5bar (50 kPa).

Store enough air

The system volume must store enough air so the failure of the biggest compressor will not impact production. The reserve volume needs to keep the system above the critical POU pressure until the replacement compressor can be brought online. Otherwise, any money saved in power by operating at a slightly lower pressure may be lost by impacts to production quality or quantity due to a lack of compressed air supply.

Action 3: Use remote pressure sensing

Fit a pressure sensor at your critical POU, connected to the compressor controller

POTENTIAL SAVINGS: 4%–15%

Remote pressure sensing allows dynamic reduction of system pressure without affecting the air pressure at the critical POU. The pressure at the compressor outlet will be adjusted automatically to account for pressure drops across your system, while maintaining the pressure at your critical POU.

Compressors load/unload depending on pressure feedback in order to maintain a pressure set point; this feedback is usually measured at the compressor outlet (see Figure 8). Instead, remote pressure sensing measures air pressure at the critical POU, not only ensuring reliability but saving compressor energy (see Figure 9).

In Figure 8, the system pressure is set at 7barg and the critical POU requires air pressure at 6barg. Depending on the load and how clean the filters are, the critical POU will receive air at 6–6.85barg, despite only needing 6barg.

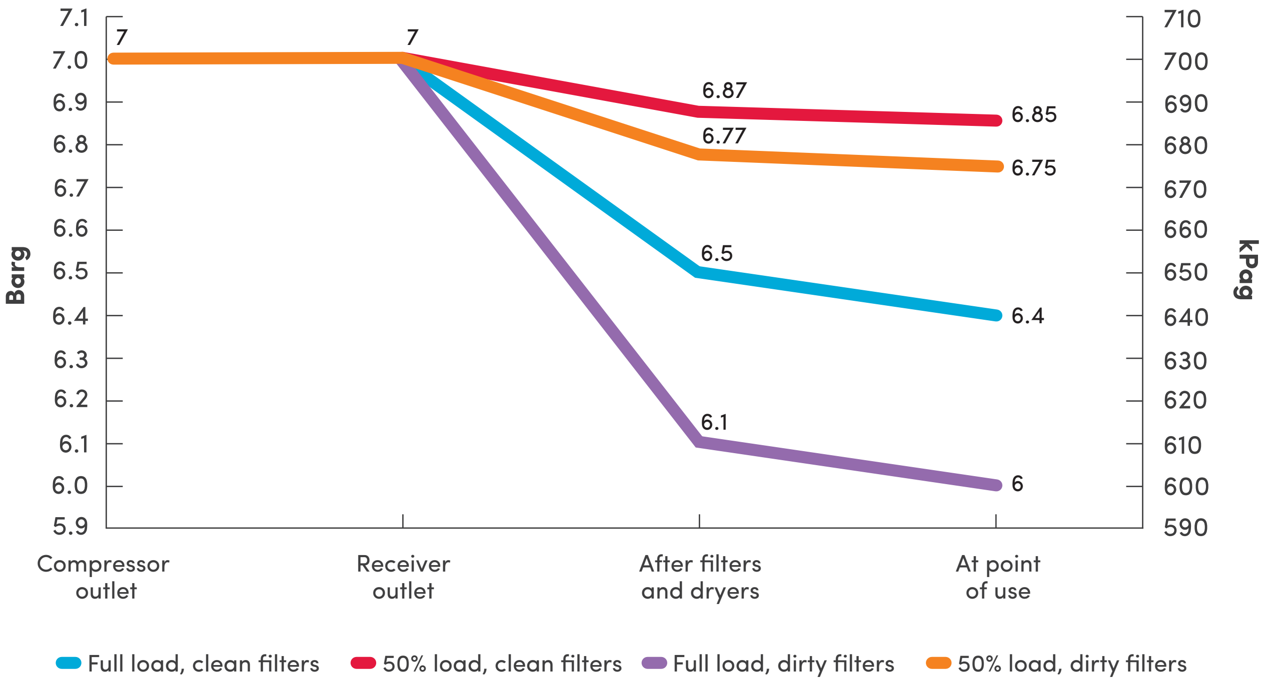

Figure 8: Variations in system pressure when based upon compressor outlet pressure

In Figure 9, where pressure is measured at the critical POU, air is supplied by the compressor at a range of pressures depending on load and filter cleanness. The air pressure at the critical POU is unaffected and maintained at 6barg and compressor energy decreased by reducing delivery pressure when possible.

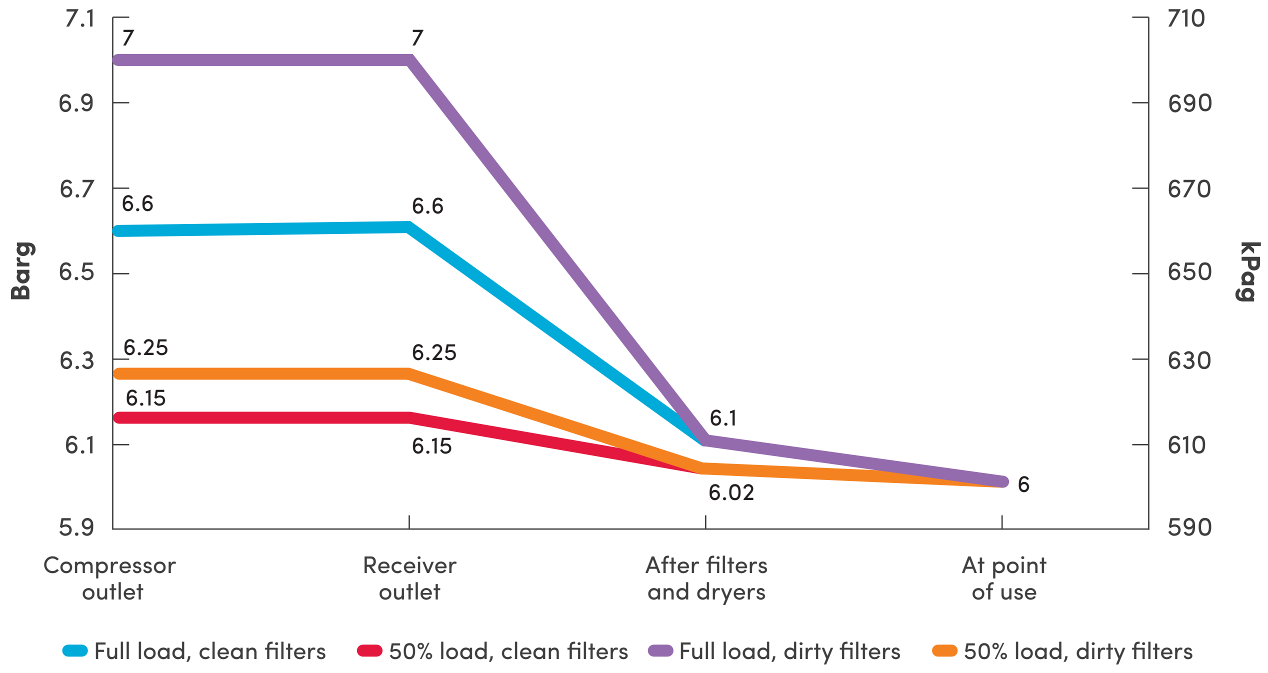

Figure 9: Variations in system pressure when based upon air pressure at critical POU

Remote pressure sensing can be achieved using several methods. Depending upon what the compressor controls support, you can control the compressor load status by:

- using an external relay/control: most compressor controllers have an input that can be wired to and directly loads or unloads the compressor. The compressor will protect itself from over pressure and will use its own sensors to do this. The external relay can be a system controller or a simple pressure switch
- fitting an extra pressure transducer to the controller: where the controller has a spare analogue input and the logic for using a remote pressure sensor. This is less common on fixed capacity compressors but standard on many VCCs.

Controlling pressure from multiple sensors

For controllers (including system controllers) using a remote pressure sensor, you do not have to be restricted to sensing the pressure at one location. There are various electronic methods of filtering the values from multiple sensors including:

- simple modules that select the minimum of a pair of sensor inputs
- small programmable logic controllers that can be programmed to do the same with multiple inputs
- larger SCADA systems that can look at multiple pressures and decide which one to act upon.

To maximise energy savings from this action, also implement **Action 2: Choose the optimal pressure band** on page 15.

Maintain your system

A regular, planned schedule of maintenance is crucial to efficient operation and the long-term reliable supply of compressed air.

Inadequate system maintenance can lead to unexpected failure of your compressors. This failure may hinder or stop normal operation of your equipment and site, and could end up being significantly more expensive than the cost of regular compressor maintenance.

Make sure your routine maintenance schedule has a suitable budget to cover the areas listed below.

Check for faulty controls

Based on survey data, between 15% and 30% of systems that appear to be operating normally actually have a compressor with faulty controls.

Action 4: Service your compressors well

At your next scheduled compressor service:

- **service inlet and blow-down valves**
- **measure motor currents**
- **clean and service the aftercooler drain**

POTENTIAL SAVINGS: 5%–20%

Air compressors are similar to cars in that regular maintenance is required based on operation hours and/or a set duration. The typical maintenance tasks can be found in your service manual and vary depending on your system.

The following tasks are not usually included in your compressor's maintenance schedule, but they affect your compressor's efficiency.

- **Service inlet and blow-down valves, and replace if required.** If an inlet valve is faulty, the compressor output will be reduced despite using more power. If a blow-down valve is faulty, the compressor will consume excess energy while unloaded.
- **Measure motor currents during the compressor load and unload cycles before and after servicing.** A service technician should be able to identify if measured motor currents are within expected ranges. Out-of-range motor currents can indicate excess energy consumption and/or inability of the compressor to deliver air at its nominal capacity. Specific out-of-range issues include:
  - high current while unloaded: a sign of an issue with the blow-down system (also indicated by longer than expected blow-down period)
  - high current while loaded: potential blockage downstream
  - low current while loaded: a sign of an issue with the inlet valve.

  To measure the unloaded motor current, the reading should be taken at least 60 seconds after the compressor unloads.

- **Clean and service the aftercooler drain.** If a drain is fitted to the compressor aftercooler, regular maintenance of the drain is required. If water is not properly removed by the aftercooler drain it can cause false pressure readings at the compressor outlet. False pressure readings can lead to high load/unload cycling frequency and insufficient delivery of compressed air to the system.

Action 5: Maintain your line filters

Check your line filters and make sure they are in good operating condition

POTENTIAL SAVINGS: 2%–15%

For filters, the necessary maintenance is periodically either changing the element or servicing the housing drain. The pressure drop across a filter increases with operating hours. Greater pressure drop in your system leads to greater energy consumption by your compressors.

The real cost of dirty filters

The pressure drop across a filter may increase from 0.5bar (50kPa) when clean, to 0.9bar (90kPa) when dirty. This extra pressure drop of 0.4bar (40kPa) typically corresponds to a 2–2.5% increase in energy consumption (at full compressor capacity).

To maximise energy savings from keeping your filters in good operating condition, do this in conjunction with **Action 2: Choose the optimal pressure band** on page 15 and **Action 3: Use remote pressure sensing** on page 19.

Tip: Replacing and upgrading filters

How often you need to replace your line filters will depend on your system, usage, ambient air conditions and your compressed air requirements. Ask your compressor service company to change your main line filters as part of your compressor service. At the same time, make sure all other filters are checked regularly and changed when specified by the filter user manual.

If you are considering a major filter upgrade, consider a depth of bed filter for the pre-filter. These filters have extremely low pressure drop (4–6 kPa) and an element life of 8 to 15 years compared to other similarly rated filters that would have higher pressure drops (20–60 kPa) and require annual element changes.

Action 6: Service and upgrade your drains

Check your drains for excessive air leaks and to make sure they are working. If they need replacing, install sensing drains

POTENTIAL SAVINGS UP TO: 20%

Drains are a crucial part of a compressed air system to remove water from the system. Even with a fully functional dryer, some water will condense in the air distribution part of the system. This condensate is predominantly water, with a small amount of oil. Drains are typically installed at multiple locations in a compressed air system allowing removal of the accumulated liquids.

Failure to remove the liquid from the system will result in:

- liquid reaching your production equipment; this may be disastrous for your process and result in increased maintenance costs and higher pressure drop. Rust particles may also block or damage equipment
- damage and clogging up of filters, which may reduce your system pressure and affect production, and increase compressor power use
- reduction of overall system volume which means your compressor will work harder to compensate.

Manually check your drain performance monthly.

Operational modes for drains

There are three operational modes for drains: manual, timed and sensing.

Manual and timed drains are usually open for longer than necessary, resulting in wastage of large volumes of compressed air. Sensing drains will open automatically when the water levels in the reservoir reach a certain set level, and they close again when the collected water has been drained. Sensing drains are the optimal drain types that remove water with little or no air wastage.

When a new drain is required, sensing drains should be used where the budget is available, and installed when there is safe access to the drainage point. Areas of high condensate flow should take priority.

There are three types of sensing drains:

- **electronic**
  - the fastest valve action, thus wastes the least amount of air
  - best installed near the compressor or dryer where it has the most secure power supply
- **mechanical**
  - can be the cheapest and no power is required
  - valve operation is slower than electronic drains, leading to more air waste
  - the valve is smaller by design, and prone to blockage
- **pneumatic**
  - similar to mechanical drains, but valves are operated pneumatically
  - compressed air supply required for operation
  - faster valve operation than mechanical drains – wastes less air and suited for high condensate flows
  - larger drain valve than mechanical drain – less prone to blockage but installation limited by space availability
  - robust and reliable – suited to installation on wet air receivers and large refrigerated dryers.

The ideal drain set-up

A good drain installation should have:

- a full flow ball valve before the strainer and drain to allow them to be isolated for servicing
- a strainer before the drain to prevent the drain valve seat from getting blocked open or closed
- a manual drain to check the drain is working correctly.

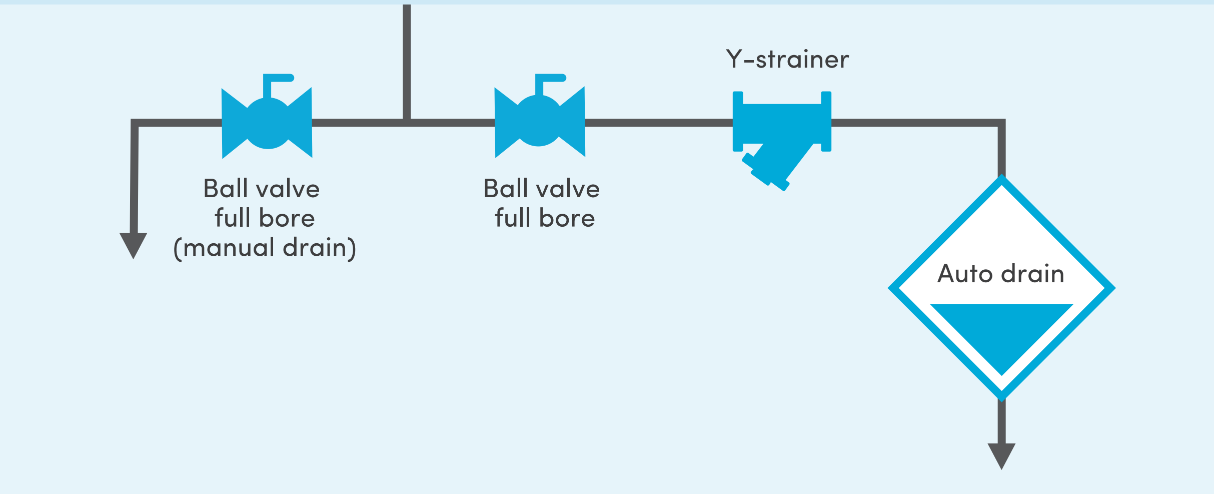

Figure 10: Main components of a good drain installation

Photo: Wat Als Photography/OEH

Automatic drain on a receiver tank

Photo: Wat Als Photography/OEH

Actions to optimise demand side

Many compressed air systems operate inefficiently. It is not uncommon for only 50% of the compressed air generated being used towards actual production. The other half is waste – compressed air usage that does not contribute to your plant's production. This waste consists of leaks, artificial demand and inappropriate uses (see Figure 11).

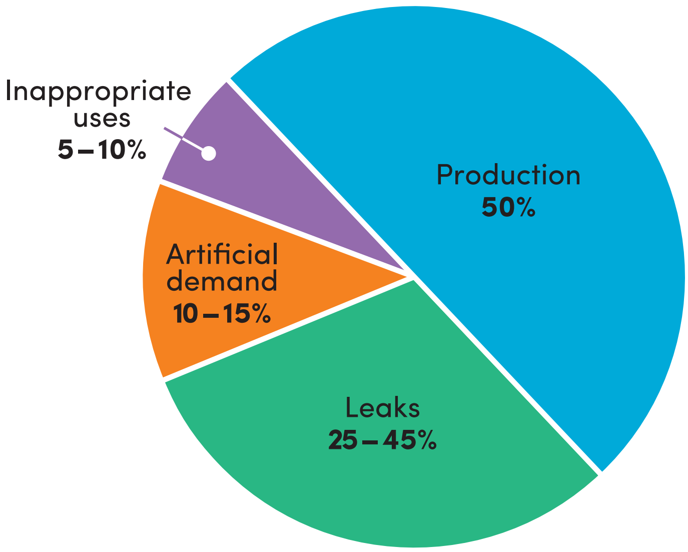

Figure 11: Typically only half the compressed air generated is used towards production

Depending on the equipment in your plant, compressed air flow outside production will be predominantly air leaks. If you haven't yet calculated how much this is costing you, see **Estimate your air usage during non-production** on page 45.

Reduce leaks

Action 7: Check and fix air leaks

Conduct in-house air leakage surveys at least every six months

POTENTIAL SAVINGS UP TO: 30%

Air leaks are common and can occur anywhere in the compressed air system. The amount of air leakage varies from site to site, but typically between 25% and 45% of compressed air is lost via leaks.

Fix leaks promptly

Maintenance and operational staff should tag and fix leaks as soon as they are located (when safe to do so) and not wait for a formal survey.

The main reasons air leaks occur are:

- wear and tear over time, through moving parts such as actuator seals, solenoid seals, air tubes and hose connections and leaking pipe joins
- mechanical and chemical damage such as to fittings mounted in low areas (e.g. gauges on pressure regulators), or through material degradation
- poor workmanship such as badly seated or damaged valve manifold gaskets, missing welds in flanges and pipe joins.

Leaks can be detected both by operators and by ultrasound detectors, as explained below.

How to find air leaks

Simple ways to detect air leaks include:

- **see:** look for symptoms; in some cases, air hoses can be seen fluttering in the fitting due to air leaks
- **hear:** listen for the characteristic hiss of leaking air where possible
- **feel:** air movement caused by a compressed air leak can be detected using a feather or wool tuft attached to the end of a pointer or similar
- **use soapy water:** a tried and true method of detecting any gas leak in any system.

Warning

Never block a compressed air flow with bare skin. Compressed air can be forced through the skin into the blood stream causing embolisms and possibly death.

A jet of leaked air can also entrain dust and other small particles. This causes a 'dust volcano' at the location of the leak. The dust volcano forms when the entrained air changes direction too quickly for some dust particles to follow, hence the dust particles hit the surface where the leak is coming out of. The dust builds up on the surface of the source of the leak.

In cases where leaked air impacts another surface, the entrained dust will result in a smudge or line. Even relatively small leaks will cause these smudges (see Figure 12).

Photo: The Carnot Group

Photo: Basil V.R. Greatrex Pty Ltd

Figure 12: Examples of compressed air leaks that impact surfaces, with entrained dust particles forming a smudge or line on the same surface

Using an ultrasound detector

When air leaks, it moves from a pressurised system to ambient pressure, and generates ultrasonic pressure waves at a frequency we can't hear.

An ultrasonic leak detector is a sensitive sound meter that can detect these frequencies. Most detectors also shift the frequency of the ultrasound so it can be heard through a set of headphones. Even small leaks can be heard from many metres away in noisy factories. Good quality ultrasonic detectors range from $2000 to $12,000. They can be hired, are easy to use and can reduce leakage to under 5%.

Professional leak detection and repair

For a fee, an experienced contractor can rapidly identify and repair a large volume of leaks as well as provide leak monitoring services.

Reduce artificial demand: pressure regulators

Photo: Wat Als Photography/OEH

Artificial demand is the air used by a process that is excess to that needed to complete the process task.

Artificial demand examples

- The air pressure is higher than that needed to operate a process. For example, an actuator only needs 5barg (500kPa) to operate with enough force and speed but is supplied with air at 7barg (700kPa). Reducing the supply pressure will reduce compressed air demand by 29% and save energy.
- Air is contained in pipes and equipment that are not part of the core process, but are used and vented when the process operates. For example, the tube volume connecting a valve to an actuator is wasted when the actuator operates. Only the volume of the actuator itself is the real process volume.
- An air-operated system operates when it is not needed. For example, a dust filter bag house can be pulsing to clean bags based on a timer, when they are already clean.

The most common sources of artificial demand are large pressure drops in regulators (regulator droop) and pressure drops related to the actuator's operation.

To identify places of artificial demand in the regulators, walk around your factory, and check the gauges on the pressure regulators. Is the gauge moving slowly, moving quickly, or steady? See Table 2.

Table 2: Observing the gauges on pressure regulators

Observation	Description
Gauge moving slowly	Air is not being regulated. The regulators may not be set up properly – see **Action 8: Check your regulator settings** on page 29.
Gauge moving quickly	This is an indication that your regulator is wasting lots of air through large pressure droop – see **Action 9: Reduce pressure drop at your regulators** on page 30.
Gauge steady	Your air is being regulated adequately.

Video record fast-moving gauges

You can video fast-moving gauges and then watch them in slow motion to better understand what is happening.

Be aware that all air demand should be properly regulated otherwise you cannot control artificial demand.

Action 8: Check your regulator settings

Check regulator operation and adjust settings to the lowest outlet pressure for the equipment to work properly

POTENTIAL SAVINGS: 5%–30%

A common case of artificial demand is caused by regulators set at a higher pressure point than required. Often these pressure settings are increased as dirty supply air filters cause pressure issues at the process, but when the filter elements have been replaced, the regulators are not adjusted back to the correct pressure setting.

Best practice is to have a display label next to each regulator supply pressure gauge that indicates:

- the minimum regulator outlet pressure at no flow
- the regulator outlet pressure setting with flow.

This will help remind you to keep the correct regulator setting.

Warning

Be careful when adjusting pressures for gripping systems (including vacuum systems), ensuring that sufficient force is maintained to handle the heaviest product the machine will encounter. This force could be needed at the point of initial pick-up or somewhere later in its movement as it is accelerated, decelerated, spun around, etc.

If you notice a regulator is broken and needs replacement, see **Buying a new regulator** below.

Action 9: Reduce pressure drop at your regulators (regulator droop)

Check regulators and try to reduce pressure drop in actuators

POTENTIAL SAVINGS: 5%–15%

- Check the regulator filter and replace it if dirty.
- Check the pipes on both sides of the regulator and measure their internal diameters. The internal pipe diameter should be three times the nominal port size of the device (directional control valve, actuator or nozzle) supplied by the regulator.
- Try to reduce pressure drop in actuators – See Table 4 on page 32.

If regulator droop is still evident, then your regulator is either undersized or poorly designed, and should be replaced.

Buying a new regulator

When buying a new regulator consider:

- using a low spring rate or air pilot design – these have no spring and so no droop due to spring rate (use for precision regulators)
- using a regulator with a higher flow rating as it will have less droop. Beware that too big a regulator may be unstable at low flows and cost more than other options
- selecting a regulator with less droop for the flow range you are handling
- fitting a bigger body regulator. Often a regulator may have three different port sizes, so make sure the body itself is bigger. This reduces spring rate and velocity effects over the same flow rate
- fitting a regulator system with external feedback. This has the added benefit of being able to correct for pressure droop depending upon where the feedback point is taken. Note the external feedback regulators may be slower to respond than normal regulators.

Regulator droop describes how much the regulator outlet pressure reduces with increased flow and forces air compressor systems to operate at a higher pressure. Reducing regulator droop allows the compressed air system to operate at a lower pressure.

Table 3 and Figures 13 to 15 show pressure droop in three different regulators flowing 1.7m^3/min at an outlet pressure of 5.2barg.

Table 3: Regulator droop in different size and type of regulators

Figure	Pilot size and type	Pressure droop	Required setting at no flow barg (kPag)	Pressure at $1.7m^3$/min barg (kPag)
14	Small body spring pilot	Large droop – 15% droop	6.2 (620)	5.2 (520)
15	Bigger body spring pilot	Small droop – 2.6% droop	5.4 (540)	5.2 (520)
16	Air pilot	No droop – 0%		5.2 (520)

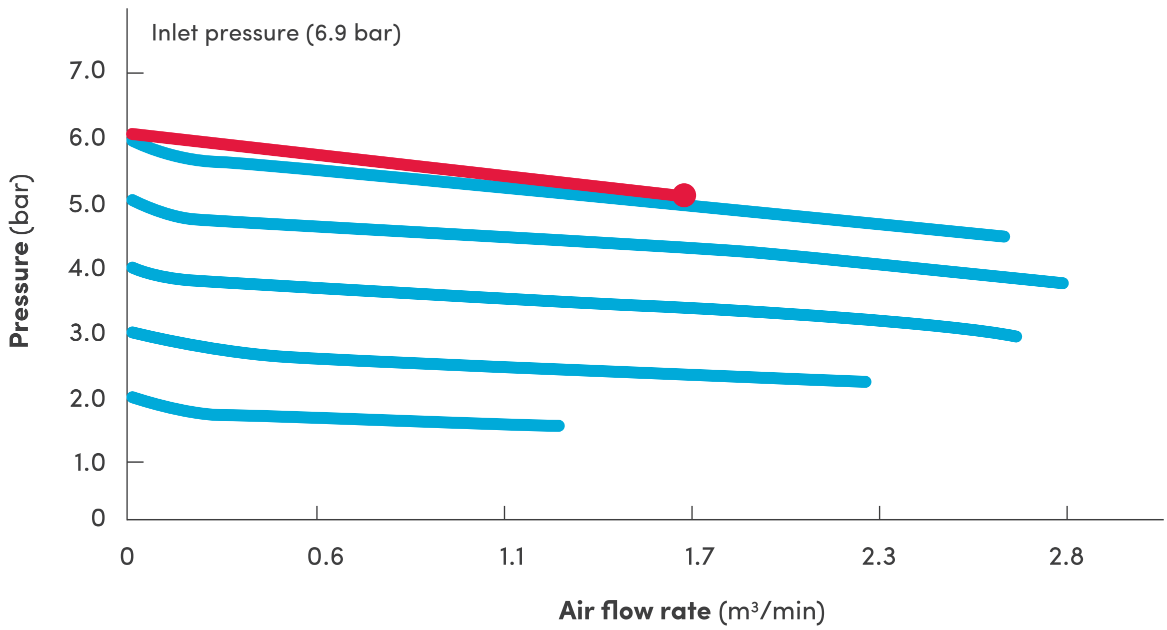

Figure 13: Small body spring pilot – large regulator droop

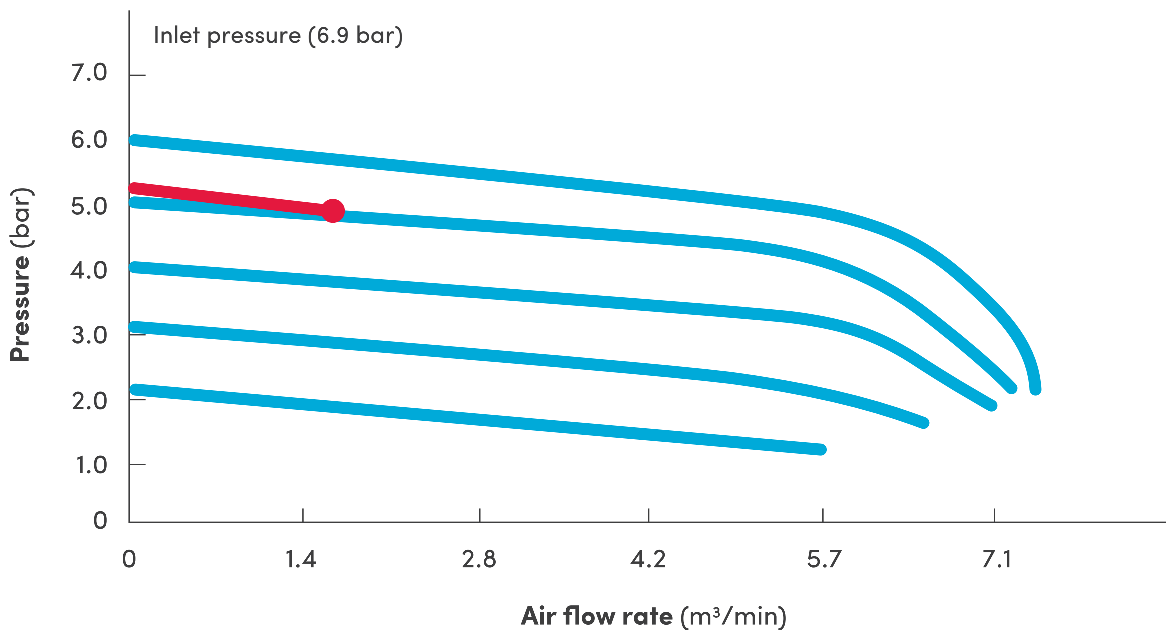

Figure 14: Bigger body spring pilot – small regulator droop

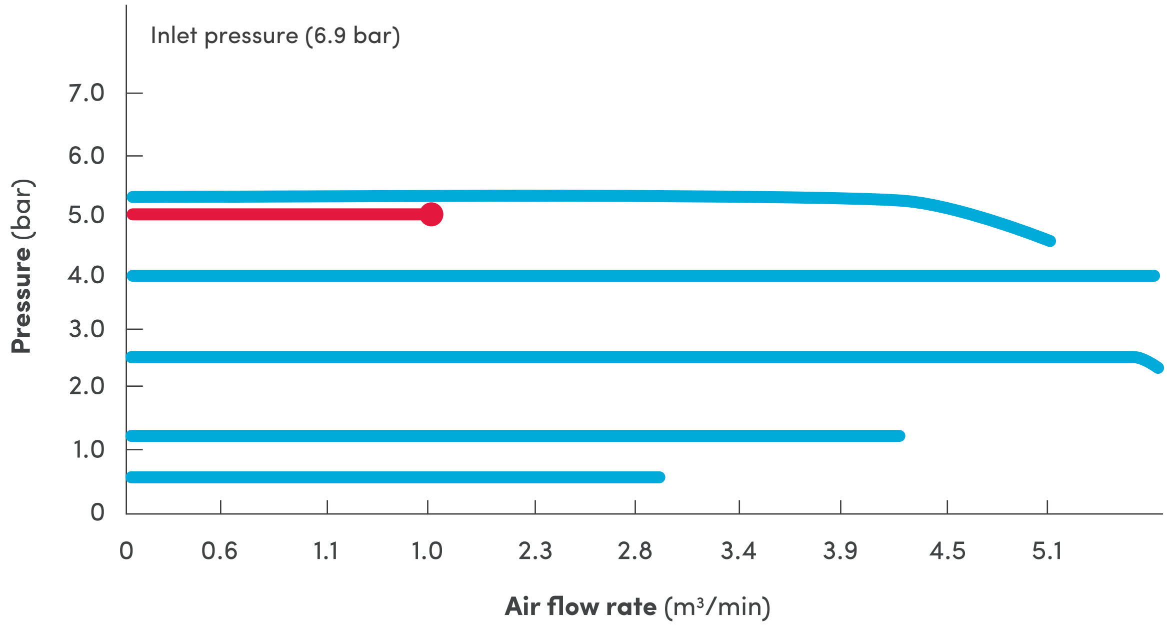

Figure 15: Air pilot – no regulator droop

The four main causes of and solutions for regulator droop are shown in Table 4:

Table 4: Causes of and solutions for regulator droop

Cause	Solution
Poor regulator design	New regulator – see **Buying a new regulator** on page 30
Wrong regulator size	New regulator – see **Buying a new regulator** on page 30
Pressure drop in actuators (high peak flows)	Optimise your actuators' operations – see Actions 10, 11 and 12 Use high-efficiency nozzles and high-efficiency vacuum venturis
Dirty upstream filters and undersized piping connected to regulator inlet and outlet	New filters, bigger pipes

Reduce artificial demand: actuators

Photo: Wat Als Photography/OEH

Once you have addressed any issues with your regulators, you can then optimise your actuators' operations.

Use Table 5 to identify and prioritise how you can best reduce pressure drop in your actuators, based on your system equipment (the actions are explained in the following sections).

Table 5: Actions to optimise actuator operations

Action	Priority
10 Tune your actuators	Tune all actuators but prioritise your largest actuators first. Where access to actuators is an issue, this should be corrected
11 Install economiser regulators	Target the heavier air users first based on number of cycles and volume per cycle
12 Reduce wasted volume in tubing	Target the regulators where the tubing volume to actuator ratio is largest. This can often be identified by the length of the tubing
13 Re-use air from actuators	Target actuators where the air can be re-used for blow-off nozzles

Action 10: Tune your actuators

Tune your largest actuators first

POTENTIAL SAVINGS: UP TO 10% OF ACTUATOR AIR USE

The approach to actuator tuning is to establish the minimum pressure required for the cushions to properly absorb the kinetic energy of the moving mechanism at normal cycling speeds without bouncing. The flow controllers and opposing pressure regulators are then adjusted up slightly so the resulting motion is sufficiently smooth.

Tune your largest actuators first, starting with the end exhausting during the main working stroke, by following these steps:

1. Screw in both cushion valves.
2. Fully open the flow controllers at both ends.
3. Set the regulator, for both ends of the cylinder, to 0.5bar (50kPa).
4. Increase the regulator after every few cycles. Oscillate the cylinder until the required working and return stroke travel times are achieved.
   - If during this process an end cushion bounces, progressively open its valve until the cylinder comes to a smooth stop.
   - With a single regulator system, if either the forward or return stroke is faster than desired, close its flow controller until the stroke is slowed sufficiently. Once the speed is sufficiently slow, you may also need to adjust the cushion valve for the exhaust stroke to ensure a smooth stop without bouncing.
5. Operate the machine with product, which may require an increase to the regulator pressure setting for the working stroke to achieve the required travel time.
6. Operate the machine without product and confirm the cushions stop the cylinder smoothly. If the working stroke is too fast, adjust its speed controller slightly.
7. Once the actuator is operating correctly, record the regulator pressure settings on or near the regulator so the setting can be easily checked.

Action 11: Install economiser regulators

Install economiser regulators for the largest actuators on site when budget permits

POTENTIAL SAVINGS: UP TO 25% OF ACTUATOR AIR USE

In many applications, the pressure required from an actuator is higher in one direction (working stroke) and lower in the opposite direction (return stroke). Consequently, the compressed air pressure required for the return stroke is lower.

Economiser regulators reduce the amount of air used by an actuator's non-working stroke. They are fitted between the directional control valve (DCV) and actuator ports. Note that any regulator being used as an economiser regulator must allow air to flow back through it when the actuator is exhausting.

The lower the pressure setting, the lower the artificial demand associated with an actuator's operation. The presence of economiser regulators will allow you to set different pressures for the working and returning strokes of an actuator.

Economiser regulator considerations

If the DCV has a dedicated regulator, the pressure at this regulator would be set at the required pressure for the working stroke. One economiser regulator would be required for the return stroke.

If the DCV has a shared regulator with other equipment, then two economiser regulators may be required, one for the pressure required for the working stroke, another for the return stroke.

Economiser regulators cost between $50 and $300. They are typically economical for large actuators (>50mm diameter).

Action 12: Reduce wasted volume in tubing

- **Move the solenoid control valve closer to the actuator, *or***
- **Install an air-piloted control valve at the actuator, using smaller air tubing between the solenoid control valve and the new air-piloted control valve**

POTENTIAL SAVINGS: UP TO 20% OF ACTUATOR AIR USE

During actuator operation, the air in the tube between the solenoid control valve and the actuator is pressurised and vented as the actuator cycles. The air inside the actuator contributes to actuator operation while the air inside the tubing does not and is wasted (artificial demand).

Moving the solenoid control valve closer to the actuator reduces wasted volume in the tube. Before doing this ensure you still have safe access to the valve when maintenance is required.

Where you can't move the solenoid control valve closer, such as on a manifolded set-up, install an air-piloted control valve at the actuator and reduce the volume (smaller diameter tube) between them.

Action 13: Re-use air from actuators

Where practical, look for blow-off nozzles that can re-use actuator air

POTENTIAL SAVINGS: UP TO 90% OF ACTUATOR AIR USE

At the end of a stroke in an actuator operation, the air pressure is normally close to the supply pressure. This air can be re-used by other processes that operate at a lower pressure. These processes can either be within the same machine or in blowing air to move, clean or dry.

As re-used air is very dry, it can be used in some applications with local membrane dryers to efficiently provide the dry air needed by clean rooms and food manufacturing processes.

There are two phases for air recovery during an actuator's movement – high flow and low flow. Up to 60% of air use can be recovered from the short, high-flow phase as the actuator blows down before it starts to move. From the longer low-flow phase as the actuator moves, air can only be re-used for blowing and should be downstream of the actuator's speed controller.

The ease of re-using air will depend on your processes and applications. In some cases, it is very simple to set up.

Reduce inappropriate use and waste of compressed air

Action 14: Find opportunities to reduce inappropriate use

Identify and reduce inappropriate uses of compressed air

DIRECT SAVINGS: UP TO 100% OF INAPPROPRIATE USE

As air is often considered ‘free’, readily available, and cheap to set up, it is often used in inappropriate applications.

Common misuses include:

- constant blowing or cleaning
- vortex (cabinet) cooling
- protecting ingress
- cooling
- drying
- lifting weights that could be spring-loaded
- cooling or cleaning personnel (this can also be a health and safety issue).

Action 15: Reduce wasted air in your vacuum systems

Minimise the duration an ejector is switched on, and minimise pressure used to drive the ejector

POTENTIAL SAVINGS: MORE THAN 60% OF AIR USED BY VACUUM DEVICES

Vacuum cups are widely used in manufacturing to hold flexible, soft or difficult-to-grip items, including cardboard boxes, plastic bags, finished products and sheets of building material. The most common way of creating a vacuum is a vacuum ejector, which uses a high-speed air jet to create a venturi effect to suck in air.

There are high and low vacuum ejectors to suit different applications. The efficiency of a vacuum ejector is how much compressed ‘drive’ air is required for a given amount of vacuum flow. Once a vacuum is reached, the ejector only needs to maintain the vacuum. The driving air supply can be reduced or stopped altogether.

Vacuum circuits can waste air in many ways:

- operating at a higher vacuum than needed
- long tubes between the air valve, vacuum generator and the vacuum cup create wasted volume and slow the operation of the vacuum system
- applying the vacuum for longer than necessary.

To minimise the duration for which an ejector is on:

- avoid waiting periods with the vacuum energised
- begin to move an item if the movement can be completed
- avoid periods where a vacuum is left on while the machine is waiting for another part of a sequence to complete; the machine sequencing or programming can sometimes be changed to minimise the waiting period.

To reduce the pressure used to drive the ejector:

- if the ejector has its own supply regulator, adjust this so only enough vacuum is generated to hold the product for the required duration; remember to include a safety factor.

Choosing multi-stage ejectors

If you are upgrading or buying a new vacuum system, multi-stage ejectors are the most efficient as they allow vacuum flow to be added at different points along the diffuser. There are high efficiency vacuum generator modules that combine multi-stage ejectors with:

- regulators that control the drive air based on the level of vacuum in the system
- check valves and other controls needed to minimise the drive air demand.

Part 2: Review your system and estimate potential savings

Photo: Wat Als Photography/OEH

Compressor system factor: understanding your system efficiency

Compressor system factor (CSF) is a simple measure of system efficiency and can be used to estimate energy use and air waste in your system. Essentially CSF measures how efficiently your compressors and system work together. It applies to all compressors that load/unload including variable capacity compressors at low loads.

Calculating your CSF can help you identify and prioritise low capital cost projects to improve the efficiency of your system, as well as providing further insight into the operation of your compressed air system. CSF is calculated with a simple formula that uses your compressor's load and unload cycle times and pressures.

Longer cycling is better

The shorter a compressor's load/unload cycles are, the higher its average unloaded power. More short cycles will use more power than fewer longer cycles for the same load. The part-load power used by a compressor is directly related to its CSF, so the more power used by the compressor operating at a given part load, the smaller the CSF.

Gather data

To calculate CSF, you need to gather the load and unload times, and the corresponding pressures of your compressor for at least four or five cycles during a period of typical production.

To collect this data, stand next to the compressor with a stopwatch or timer and record when it loads and unloads as identified by a change in sound or by viewing the pressure changes in the gauges. Often, load status is shown on the compressor control panel together with the required pressures, and both can be recorded in a data collection table similar to Figure 16 (see Appendix 2 for a template of this table). Figure 16 shows an example of these measurements for a 45kW compressor.

Sometimes flow isn't on a compressor's data plate. If it isn't, look at a brochure for the compressor and its pressure rating or ask your service company.

Make and model number			Model T1000 / make	
Compressor data plate motor power			45kW	
Compressor data plate rated flow and pressure			8.2 m^3/min – 7.5barg	
Compressor loads	**Compressor unloads**	**Pressure barg**	**Loaded seconds (T_L)**	**Unloaded seconds (T_U)**
10:27:44		6.8	6	
	10:27:50	7.1		17
10:28:07		6.8	5	
	10:28:12	7.1		17
10:28:29		6.8	5	
	10:28:34	7.1		17
10:28:51		6.8	5	
	10:28:56	7.1		17
10:29:13		6.8	6	
	10:29:19	7.1		18
10:29:37				
Values to be used in CSF		**6.8 –7.1**	**5**	**17**

Use the values that are measured as the system delivers consistent load and unload cycle times.

Figure 16: Example data collection table

Estimate your compressor duty cycle and CSF

The CSF is simply the percentage of a compressor's capacity per minute stored and released by the system during each load/unload cycle, and its units are a percentage of a minute. The larger the CSF of a system, the longer the compressor cycle time for a given load. CSF can be defined as:

$$CSF = \frac{T_U \text{ x } \%DC}{60}$$

Where:

- $\%DC$ is the compressor percentage duty cycle or average load at the time of the reading
- T_U is the time spent unloaded (including compressor blow-down) in seconds.

At the same time the compressor's percentage duty cycle (%DC) can be found from the following equation:

$$\%DC = \frac{100 \text{ x } T_L}{(T_L + T_U)}$$

Where:

T_L is the time spent loaded (including delivery air and pump-up time) in seconds.

See Figure 18 for an illustration of compressor cycling.

Note that if a compressor stays loaded for more than five minutes then it can be considered fully loaded ($\%DC$ = 100).

Worked example B:
Calculating duty cycle and compressor system factor

Q: Estimate the duty cycle and the CSF for the 45kW compressor from Appendix 3 where:

- T_L is 5 seconds
- T_U is 17 seconds.

A: Using the DC and CSF equations:

$$\%DC = \frac{100 \text{ x } 5}{(5 + 17)}$$

$$\%DC = 23\%$$

Then,

$$CSF = \frac{17 \text{ x } 23\%}{60}$$

$$CSF = 6$$

CSF savings potential and priority areas

You can use the CSF value to prioritise which low capital cost, simple-to-do actions to focus on:

CSF	Savings potential of CSF-related actions	Priority areas
< 15	High	See **Actions to optimise supply side: Compressor house operations** on page 8
15–40	Moderate	
40–60	Low	See **Actions to optimise demand side** on page 25
60+	Very low	

In any system, the CSF is proportional to the ratio between the amount of air stored and released in each cycle and the trim compressor's full-load capacity.

CSF can also be used to assess the efficiency of potential improvement measures such as adding storage receiver capacity, changing pressure bandwidths, or switching to different compressor control modes. For more detailed information on CSF and its application, see Appendix 1.

Estimate your compressor power consumption and cost

Your compressor power consumption and cost can be calculated using CSF values and the information you have already collected. The following graph models compressor efficiency curves and relates the effect of CSF (system volume and pressure band) and compressor load on compressor power consumption. See Appendix 3 for a larger version of this image.

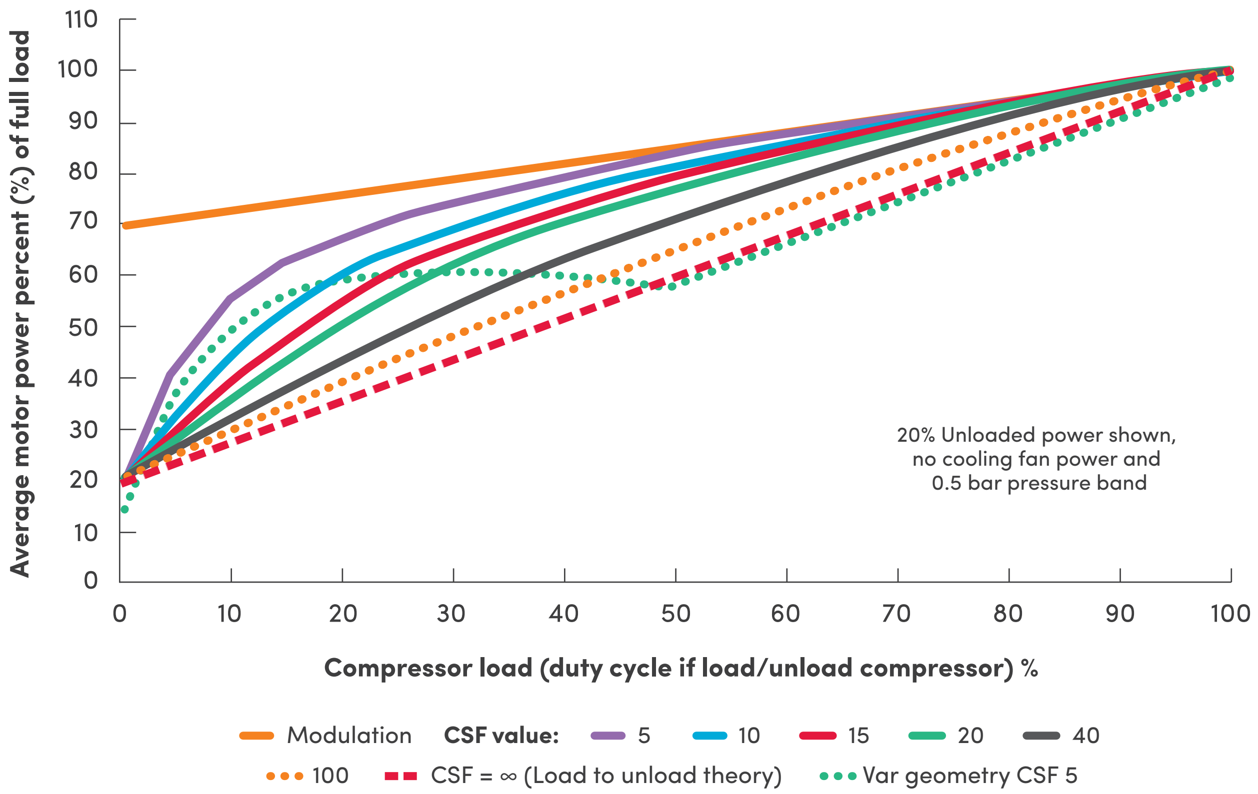

Figure 17: Oil flooded, rotary screw compressor efficiency curves for different loads and CSF values

To calculate the average power consumption of any compressor, use the formula:

Average Power Consumption (kW) = Average Motor Power Percent (%) x *Nominal Power (kW)*

Where:

- average motor power percent (y-axis) is taken from Figure 17 using calculated duty cycle and CSF
- nominal power is from the motor data plate.

You can now calculate power consumption of the compressor over a period of time:

Average Energy Consumption (kWh) = Average Power Consumption (kW) x *Operating Hours*

To calculate cost:

- obtain your electricity tariff ($/kWh): An approximate tariff is your latest electricity bill's cost ($) divided by total electricity usage (kWh)
- use your compressor's annual energy consumption (kWh) from above.

The electricity cost of your compressor over the nominated period of time is:

Compressor Electricity Cost ($) = Energy Consumption (kWh) x *Electricity Tariff ($/kWh)*

Worked example C:
Calculate compressor power consumption and cost

Calculate power consumption and cost for the 45kW compressor from Figure 17 where:

- %DC is 22%
- CSF is 6.

From Figure 17, the average power of the compressor is approximately 68%. Note that to find a CSF of 6 in the graph, you need to estimate a point between the CSF 5 and 10 curves.

The compressor in this example has a 45kW nominal rating, so its average power consumption at this load:

$$= 68\% \times \frac{45}{100}$$

$$= 30.6 \text{ kW}$$

In this case, the system operates for 12 hours per day Monday to Friday, 50 weeks per year, the total annual operation hours are:

$$12 \times 5 \times 50 = 3000 \frac{\textit{hours}}{\textit{year}}$$

So the total power consumption is:

$$30.6 \text{ kW} \times 3000 \frac{\textit{hours}}{\textit{year}} = 91{,}800 \frac{\textit{kWh}}{\textit{year}}$$

Using a tariff of $0.17 per kWh then:

$$91{,}800 \frac{\textit{kWh}}{\textit{year}} \times \frac{\$0.17}{\textit{kWh}} = \frac{\$15{,}606}{\textit{year}}$$

The annual electricity cost of this compressor is $15,606

Compressor controller timers

Compressor controllers usually have an 'HOURS RUN' timer and a 'LOADED HOURS' timer that will allow you to gather data for longer periods of time, such as a shift. You can use this information to obtain a more accurate picture of your system performance and your power consumption.

Real power metering

The most accurate way to determine your air compressor system's power consumption is to measure the real power consumed by your system.

Temporary real power meters are relatively cheap to hire, and data collected over one production cycle, e.g. one to two weeks, can be extrapolated to annual energy consumption.

Estimate your air usage during non-production

Your non-productive air usage will include:

- air leaks
- production equipment left running when it should be off
- services left running when they are not required, e.g. bag house type dust collectors with pulse systems
- controllers of production equipment that lose their programming.

To estimate your non-productive air usage, follow the same data collection process described in **Gather data** on page 40 for all compressors during a period of non-production, and then calculate your average flow:

$$Q_{AV} = Q_R \times \frac{\%DC}{100}$$

Where:

- Q_{AV} is the compressor's average flow
- Q_R is the rated compressor flow in m^3/min
- $\%DC$ is the compressor % duty cycle.

Add up the flows for all of the compressors running during the test. This is the average system demand at the non-production time, which equals the amount of air being wasted.

Ideally, only one compressor is cycling and all other compressors are either off or fully loaded ($\%DC$=100, $Q_{AV} = Q_R$).

The cost of this wasted air during non-production can be calculated by following the method outlined above in **Worked example C: Calculate compressor power consumption and cost** on page 44. If more than one compressor is running, then you need to add together the power consumed by each of them. For any compressor that is cycling (load/unload), use individual CSF values to estimate power as described previously.

More information

Surveys

To find further efficiencies you can engage an independent compressed air professional to carry out a survey of your compressed air system. A survey will identify where and how your system can be more efficient, while ensuring reliability and production requirements are met. Be aware that 'free' surveys from equipment suppliers can be used to sell new compressors and other equipment rather than focusing on improving your existing set-up and equipment.

As a minimum, a good survey will measure compressor pressure and power at one second intervals which is fast enough to properly capture the interactions between the compressors and the air system.

NSW Government Energy Savings Scheme

The NSW Government **Energy Savings Scheme** (ESS) is an energy efficiency trading scheme that offers financial incentives to organisations who invest in energy savings projects. These incentives, awarded based on how much energy you save, are in the form of energy savings certificates (ESC) and are typically paid after projects have been implemented. Depending on the size of your system and your savings, ESCs can be a valuable mechanism to help pay for your improvement projects. To find out more about the potential ESC value from your projects, talk to an **Accredited Certificate Provider**.

Additional resources

For more information on compressed air system efficiency see:

- **Compressed Air Best Practices**
- **Compressed Air Challenge**

Appendix 1: Understanding system efficiency – Compressor system factor

The compressor system factor (CSF) measures the interaction between a compressor and its system. It is calculated as a percentage of a minute (CSF of 1 = 1%). It indicates how much of the compressor's capacity is stored and released by the system each time it loads and unloads. The more air stored, the longer it is before a compressor needs to load again.

For example, a CSF of 10 would indicate that a system had enough stored air to operate for 6 seconds at the same air demand as the compressor's rated output.

Longer cycles, higher CSF means lower power consumption

Figure 18 shows the power consumption of a 37kW trimming compressor during operation (load/unload). It demonstrates that for a given air demand, the shorter the cycles, the higher the average unloaded power. More short cycles will use more power than fewer longer cycles for the same load.

As the part-load power used by a compressor is directly related to its CSF, the more power used by the compressor operating at part load, the smaller the CSF.

Note that if the system storage is large, or the pressure band is wide, it takes a longer time for the compressor to increase the system pressure from the load to the unload setting. It also takes a longer time for the demand to use up the stored air, causing the pressure to drop to the load setting. This will result in a larger CSF.

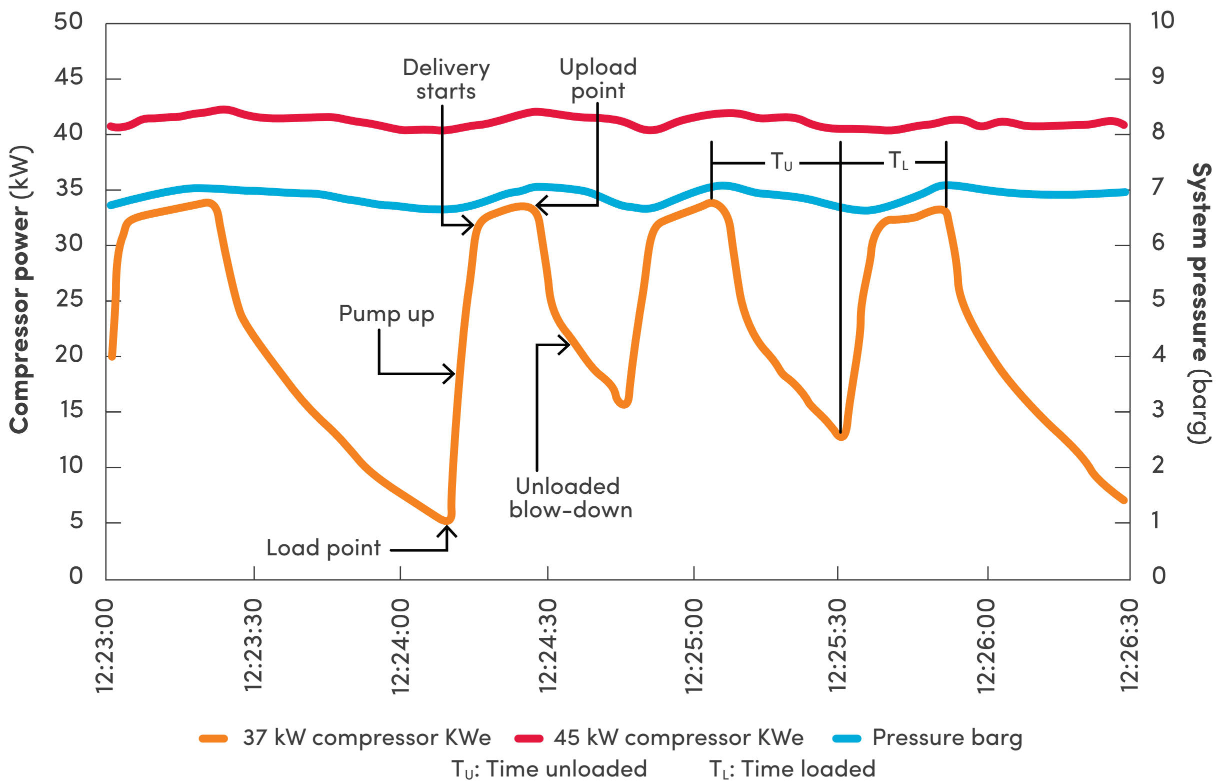

Figure 18: Power and system pressure during operation of a 37kW trimming compressor

Figure 18 shows:

- for the first and last cycles, the compressor is unloaded for a longer time and its power drops, resulting in a lower average unloaded power. For the shorter cycles, the power does not drop as far, resulting in a higher average unloaded power.
- the compressor is only producing air at the peaks of the power curve (i.e. between the 'delivery starts' and 'unload point') where power and pressure both increase together. The power used by the compressor at any other time – blow-down and pump-up – is wasted
- the power consumption of the 45kW compressor is affected by the loading and unloading points of the trimming compressor (**Action 2: Choose the optimal pressure band** takes this into account).

Using CSF to assess your savings opportunities

In any system, the amount of air stored and released in each cycle depends on the effective system volume, including the air storage receivers and the width of the load/unload pressure band. Therefore, CSF can be defined as:

$$CSF = 100 \times \frac{V_{ST}}{Q_R}$$

Where:

Q_R is the trimming compressor rated flow in m^3/min

V_{ST} is the volume of air stored by the system per cycle at 1bar (m^3 x bar). It is defined as:

$$V_{ST} = V_{EFF} \times (P_U - P_L)$$

Where:

V_{EFF} is the effective system volume and is defined as:

$$V_{EFF} = \frac{CSF \times Q_R}{P_U - P_L}$$

P_U is the compressor unload pressure, in barg

P_L is the compressor load pressure, in barg.

For systems with small demand-side stored volumes, you can use your wet receiver volume instead of effective system volume. For larger systems you will need to calculate the effective system volume.

Almost every aspect of operating a compressed air system has impacts on the CSF value of the trimming compressor. Some of the common items that affect CSF are:

- **compressor size:** CSF is based on compressor size relative to the system volume; a smaller compressor will have a higher CSF value and be more efficient at trimming the system than a bigger one
- **compressor pressure band:** the compressor pressure band directly affects how much air is stored by the system; wider pressure band will increase your stored volume and therefore improve CSF
- **pressure drop (when loaded) from the compressor to the wet receiver:** pressure drop between the compressor and the first (usually wet) receiver directly reduces the pressure band seen at the receiver; too much pressure drop will cause a compressor to short cycle and will

reduce your CSF (It is not uncommon for more than 30% of the pressure band to be lost by pressure drop between the compressor and the wet receiver.)

- **wet receiver volume:** increasing the size of the wet receiver directly increases the effective system volume therefore improves your CSF
- **wet-side to dry-side (air treatment) pressure drop:** pressure drop across the air dryer and its upstream and downstream filters reduces how much of the compressor pressure band reaches the dry-side system volume; this impacts the amount of air stored in the dry side each cycle, reducing the effective system volume and reducing the CSF
- **piping pressure drop:** any pressure drop affects how downstream volume can store and release air as a compressor cycles, hence all piping pressure drops affect CSF to a small or large extent.

Worked example D: Calculating energy savings by increasing compressor pressure band

Q: Determine the energy savings (if any) by increasing the unload pressure to 7.5barg in the following system:

- duty cycle is 22%
- the CSF has been calculated as 6
- the compressor has a rated flow of 8.2 m^3/min
- load pressure P_L was noted as 6.8barg
- unload pressure P_U was noted as 7.1barg
- average compressor power consumption is 30.6kW.

A: Calculate the effective system volume with the current pressure settings as follows:

$$V_{ST} = CSF \times \frac{Q_R}{100}$$

$$V_{ST} = 6 \times \frac{8.2}{100}$$

$$= 0.49\ m^3$$

$$V_{EFF} = \frac{V_{ST}}{P_U - P_L}$$

$$V_{EFF} = \frac{0.49}{7.1 - 6.8} = 1.64\ m^3$$

Calculate the volume stored by the system with the increased pressure band followed by the CSF as:

$$V_{ST}new = 1.64 \times (7.5 - 6.8)$$

$$= 1.15\ m^3$$

$$CFNnew = 100 \times \frac{1.15}{8.2}$$

$$= 14$$

Find the new average power consumption and compare it with the original.

Based on Appendix 3, with a CSF of 14 and a 22% duty cycle, the average motor power is 59%, so the compressor's average power is:

$$= \frac{59}{100} \times 45$$

$$= 26.6\text{kW}$$

The energy savings due to the increased unload pressure of the compressor is:

$$= 30.6\text{kW} - 26.6\text{kW} = 4\text{kW}$$

This is a 13% energy saving.

Worked example E:
Calculating energy savings by increasing effective system volume

This example is based on a real-life case study. It demonstrates how CSF can be used to evaluate performance and quantify savings.

A factory has two screw compressors (1 x 15kW and 1 x 18kW), and each compressor has its own receiver and refrigerated dryer. The receivers are 550L (0.55m^3) and 924L (0.924m^3) respectively. Both compressors are set up to supply air to factory equipment as shown in Figure 19.

Due to a decline of production, only the 15kW compressor will be required to run and will supply air at 2.5m^3/min – the 18kW air compressor will be used as redundancy.

In order to optimise the system, engineers proposed to link both systems with a plastic pipe allowing filters and dryers to service either of the compressors, increasing volume capacity as shown in Figure 20. Providing extra flow capacity and storage volume will not only decrease power consumption of the compressor, but will also decrease the wet–dry system pressure drop. This pressure drop might translate into a decrease of the compressor pressure band and could realise further energy savings.

The plant manager would like to quantify what energy savings can be achieved (direct and indirect) and whether the pressure band on the compressor should be adjusted after installation.

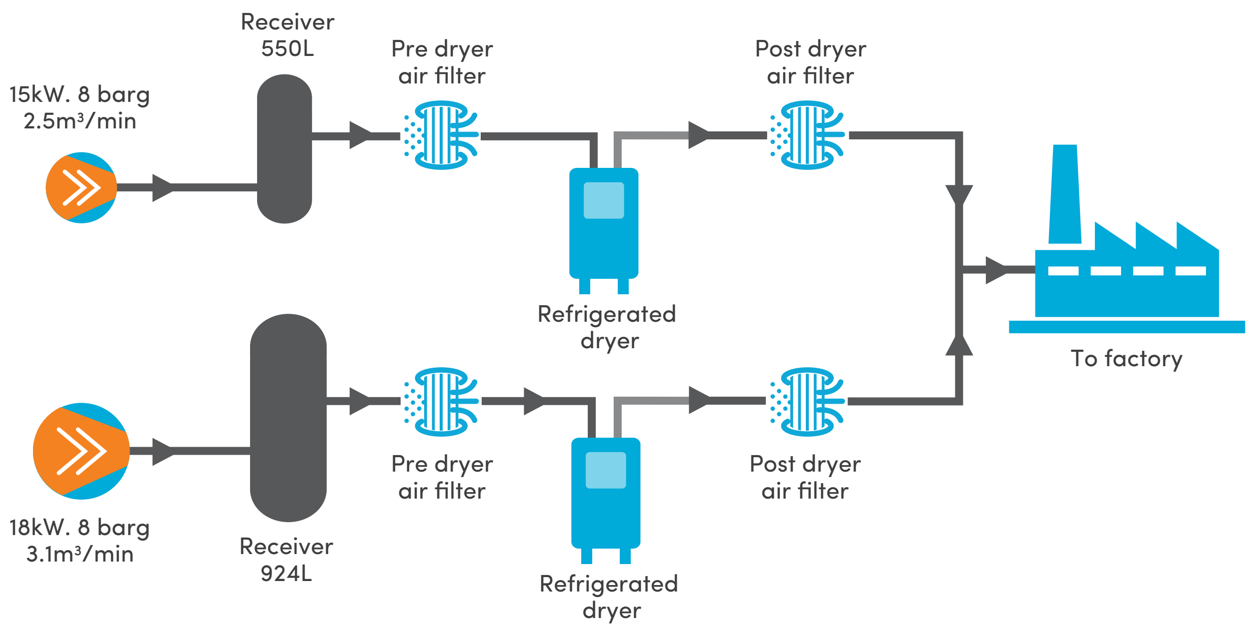

Figure 19: Original factory set-up

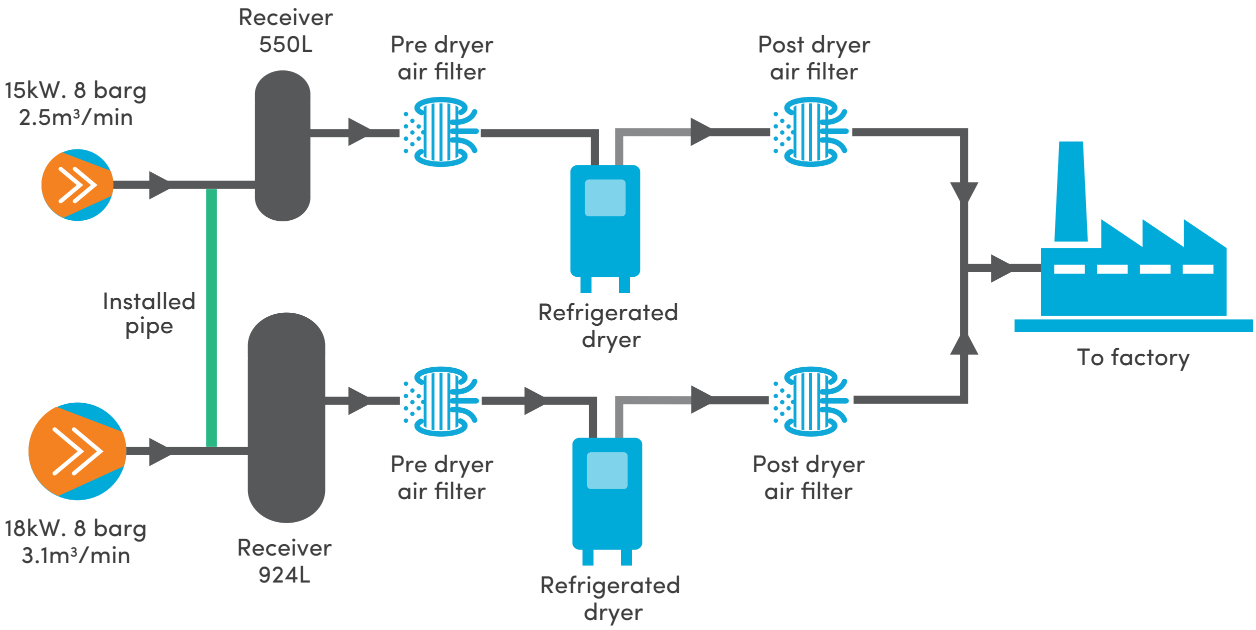

Figure 20: Factory set-up after pipe installed

Direct savings

To estimate CSF of the system running with 15kW air compressor only, data has been recorded as follows:

Compressor loads	Compressor unloads	Pressure barg	Loaded seconds (TL)	Unloaded seconds (TU)
10:12:33		7.1		
	10:13:18	8.0	45	
10:14:03		7.1		45
	10:14:51	8.0	45	
10:15:33		7.1		45
	10:16:18	8.0	45	
10:17:03		7.1		45
	10:17:48			

The duty cycle (%DC) of the system is:

$$\%DC = 100\ x\ \frac{T_L}{T_L + T_U}$$

$$\%DC = 100\ x\ \frac{45}{45 + 45} = 50\%$$

The CSF is calculated as:

$$CSF = \%DC\ x\ \frac{T_U}{60}$$

$$CSF = 50\ x\ \frac{45}{60} = 38$$

The volume of air stored by the system per cycle (V_{ST}) is:

$$V_{ST} = CSF\ x\ \frac{Q_R}{100}$$

$$V_{ST} = 38\ x\ \frac{2.5}{100} = 0.95\ m^3$$

The effective system volume (V_{EFF}) is:

$$V_{EFF} = \frac{V_{ST}}{(P_U - P_L)}$$

$$V_{EFF} = \frac{0.95}{(8.0 - 7.1)} = 1.06\ m^3$$

With the new configuration, both receivers will have the same pressure band of 0.9bar (8 – 7.1 = 0.9). Therefore, the new effective system volume (V_{EFF} *new*) can be calculated as:

$$V_{EFF}\ new = 0.55 + 0.924 = 1.47\ m^3$$

This is 39% larger than the calculated effective system volume for the original system configuration.

The new CSF (*CSFnew*) value is 39% proportionally larger:

$$CSFnew = 1.39 \times 38 = 53$$

To calculate savings, estimate power consumption from Appendix 3 as follows:

- with a CSF of 38 and a %DC of 50%, the full power is 73%
- with a CSFnew of 53 and a %DC of 50%, the full power is 70%.

This is a 3% saving of full-load power, which is a 4% saving in actual power being used.

Indirect savings

The pressure drop of the wet–dry system needs to be estimated to assess whether the pressure band of the compressor should be reduced accordingly.

The volume of air stored by the 15kW receiver ($V_{ST}15$) is:

$$V_{ST}15 = V_{EFF}15 \text{ x } (P_U - P_L)$$

$$V_{ST}15 = 0.55 \text{ x } (8.0 - 7.1) = 0.495 \text{ m}^3$$

As the effective system volume is larger than the capacity of the 15kW compressor's wet receiver, the extra volume must be stored in the 18kW wet receiver (0.924 m^3). This means that:

$$V_{ST}18 = V_{ST} - V_{ST}15$$

$$V_{ST}18 = 0.95 - 0.495 = 0.455 \text{ m}^3$$

The pressure drop at the 18kW receiver is:

$$V_{ST}18 = V_{EFF}18 \text{ x } (P_U - P_L)$$

$$(P_U - P_L) = \frac{V_{ST}18}{V_{EFF}18} = \frac{0.45}{0.924} = 0.49 \text{ bar}$$

The difference in the pressure bands of the 15kW compressor (8.0 – 7.1 = 0.9bar) and the 18kW receiver (0.49bar) is due to the pressure drop across the filters and dryer for the 15kW side. This is 0.4bar or 40kPa which is not a particularly a large pressure drop, however, only 48% (0.455 / (0.495+0.455) = 0.48) of the air is flowing through it. The rest is being stored in the 15kW receiver.

By linking the receivers, air would flow equally through both receivers; that is 50% of air flow through each. Considering that pressure drop varies proportionally with the square of flow, it is safe to assume that halving the flow rate would reduce pressure drop to a quarter or 25% of what it is without the new pipe; in this case 10kPa (40/4 = 10). The average dry-side system pressure will increase with the new lower pressure drop across the paralleled filters and dryers.

Two scenarios

Two scenarios are examined to determine whether the pressure band should be reduced:

- **Keeping the pressure band the same**

  This approach will provide direct savings from improving the CSF value of 4% as calculated above.

  However, the increased average system pressure will reduce these savings by increasing the compressor loaded power consumption and may increase the air wasted by unregulated leaks and artificial demand.

  Assuming the system has a lot of leaks and unregulated loads, the air demand will go up as the artificial demand increases with average system pressure. An increase of 30kPa on a 7barg dry system (0.3/2 = 0.15bar) pressure will increase artificial demand by 0.15/7 = 0.02 (2%). This will increase the average load on the compressor from 50% to 51% and will have a less than 2% increase in power.

  The overall energy saving will be around 2%.

- **Reducing the pressure band by lowering the unload pressure**

  This approach won't provide any direct savings from the improved CSF (4%) value but it will provide indirect savings by reducing any air wasted by unregulated leaks and artificial demand, and the compressor loaded power consumption.

The indirect savings from reducing the artificial demand due to a lower average system pressure will be around 2% of the air being used (1% of compressor capacity). The energy saving from reducing demand from 50% to 49% will be approximately 0.7% of the power being used.

The direct savings from running at the lower average system pressure only applies to the 50% of the time the compressor is loaded.

At 7barg, a 0.15bar average pressure saving is a 1% saving to the power used when the compressor is loaded. For this CSF and load, the loaded power is approximately 68% of the power used. So the direct savings in terms of compressor power will be 0.68% of the power being used.

Therefore, the overall energy saving if the average system pressure is lowered to maintain the same CSF value will be 0.7 + 0.68 = 1.4%.

Conclusion

These two scenarios show it is more efficient (2% saving compared to 1.4%) to maintain the pressure band and take the benefit of the direct savings from the improved CSF.

In addition:

- there should be no leaks on the supply side of the air system to cause increased flow with increased pressure
- any air use on the demand side, including leaks, should be downstream of a properly set, low droop regulator, so the demand-side flow shouldn't increase with the increased system pressure.

Further analysis

When the 15kW compressor loads, the pressure shown on its display will be only slightly above the dry system pressure.

While unloaded, air would flow between the receivers until their pressures are equal. At the point just before the compressor loads, the receivers will be supplying air in proportion to their combined volume. The 15kW receiver is 550 / (550 + 924) = 0.37 (37%) of the combined volume.

So the flow just before the 15kW compressor loads will be 37% of the 50% average load, so 18.5% of the compressor's rated flow or (18.5/48 = 39%) of the peak flow it is seeing when the 15kW compressor is loaded.

A flow of 39% is a pressure drop of 0.39 2 = 0.15 x the peak pressure drop (40kPa).

The pressure drop just before loading is then 6kPa (0.06bar).

The dry system pressure when the compressor loads would then be 7.1barg – 0.06 which is approximately 7.0barg.

This example shows how reducing the pressure drop between the outlet of the trimming compressor and dry-side system volume can increase the effective system volume, improve the CSF value and reduce power consumption. Here, reducing pressure drop was done by making a piping change. Other ways include changing line filter elements more often and, if buying new filters or dryers, installing oversized equipment that will have lower pressure drop.

Appendix 2:
Compressor data collection table

Make and model number:				
Compressor data plate motor power:				
Compressor data plate rated flow and pressure:				
Compressor loads (time)	**Compressor unloads (time)**	**Pressure (barg)**	**Loaded seconds (T_L)**	**Unloaded seconds (T_U)**
Values to be used in CSF				

Appendix 3: Compressor efficiency according to CSF