# UNDERSTANDING COMPRESSED AIR SYSTEM ENERGY AND EFFICIENCY

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## 1 INTRODUCTION.

Energy efficiency (EE) has a central role in tackling climate change. It is often referred to as the "First Fuel" as it is the fuel you do not have to use. EE initiatives are often the most cost-effective way to reduce greenhouse gas emissions. They allow energy delivery systems to be smaller and cheaper. The savings in infrastructure costs pay for the EE works, let alone the actual energy savings value.

The Energy Efficiency Impact Report from the USA estimates that energy efficiency initiatives can reduce Greenhouse Gas emissions by 50% by 2050. A widely accepted estimate is that compressed air accounts for an average 10% of all industrial electricity consumption. So compressed air related EE projects have an essential role to play economically and environmentally.

This article seeks to:

1. Better inform the discussion about the efficiency of a compressed air system (CAS) so that the economics around compressed air EE are properly determined and sound.
2. Show how calculating CAS efficiency using an "electrical and thermal energy balance method" is flawed. The correct method is to calculate how much work is delivered by an air using device compared to the electrical energy supplied to the compressor.
3. Provide a more informed description of what affects the conversion efficiency of a CAS:
    - Compressor waste heat, where does it go and how much can be recovered.
    - How advanced pneumatic design can improve the efficiency of pneumatic actuators.

A Compressed Air System:

- Contains compression and expansion devices and heat exchangers (coolers).
- Is an open cycle heat pump. The first mechanical refrigeration systems used air cycles.

Electrical energy is converted, by the compressor, into pressurised volumes of air. The devices using the compressed air (including leaks) are expansion devices that convert the energy in this pressurised volume back into mechanical energy (work) be it moving an object, creating a vacuum, cleaning a surface, or providing a supply of chilled air. If a device does not use any air despite being at pressure it doesn't use any energy to maintain that pressure e.g. a car tyre.

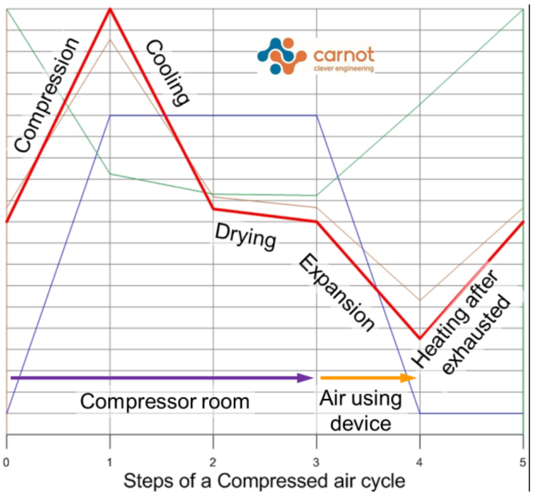

**Figure 1: Steps of a compressed air cycle**

Figure 1 shows the main steps in a compressed air cycle. These are discussed in detail in section 2.

Calculating energy savings in a CAS for any EE activities depends upon whether the project is on the "supply side" (compressor room and air mains) or the "demand side" (equipment using the compressed air:

- For supply side projects.
  The data required is the air compressor room plants average specific power values before and after any changes e.g. kWh/m$^3$ or kWe/m$^3$/min.
  Where the compressed air system interacts with another energy system, e.g. hot water via a heat recovery system, the combined systems' energy costs need to be considered. There may be a lower energy cost for the combined system if the air compressors are run less efficiently to increase the amount of heat recovered. Beware of the different tariffs between, say, electricity and natural gas when assessing the best way to operate the combined system.

- For demand-side projects the data required is :
  1. The Savings Yield is the electrical energy savings (kWh) per air volume air (m$^3$, ft$^3$) saved.
  2. How many "units of air volume," e.g. m$^3$/min of CFM were saved by the EE project. This is the difference in device compressed air use before and after any changes.

The units used for Savings Yield and Specific Power are the same, e.g. kWh/m$^3$ or kWe/m$^3$/min. While the two metrics share the same units, only in the case of a compressor operating on a variable speed drive (VSD) will they be similar in value. Savings Yields for fixed speed oil-flooded rotary screw compressors can vary between 30 and 60 % of the full load specific powers. For variable capacity machines, including those with VSDs, it could be as high as 100 %. To learn more about what affects a compressors average Specific Power and Savings Yield, refer to the article found here.

To provide a guide for what can be saved from CAS EE projects, CAS “efficiency” is sometimes stated. For example, “air motors are only 10 - 20 % efficient” is based on:

- How much shaft power an air motor generates when supplied with a compressed air flow at a certain pressure. This information would be taken from say an air motor catalogue data.
- Divided by how much electrical power a compressor needs to use to supply that flow rate of compressed air at the same pressure. This needs to assume a compressor-specific power, e.g. kWe/m$^3$/min or kW/100CFM (usually at full load).

  The power savings from replacing the air motor with an electric one would need to consider the compressed airflow to the air motor, the CAS Savings yield, and the new electric motor's power draw. The power savings, instead of being 80 - 90 % as one may think could be only 25 - 50 %.

The definition of Efficiency is work out divided by energy in.
There is no single efficiency value for a CAS system. The efficiency is specific for each device using compressed air as each device will produce different amounts of work from the same flow of compressed air at the same pressure (i.e. power into the compressor room).

A CAS's efficiency is often miscalculated by only considering the energy supplied to the air compressor and the heat rejected by it. This approach grossly underestimates the conversion efficiency of a CAS. It could result in honest and well-meaning people overestimating the energy savings from some compressed air EE works to the point of being fraudulent.

# 2 THE COMPRESSED AIR CYCLE

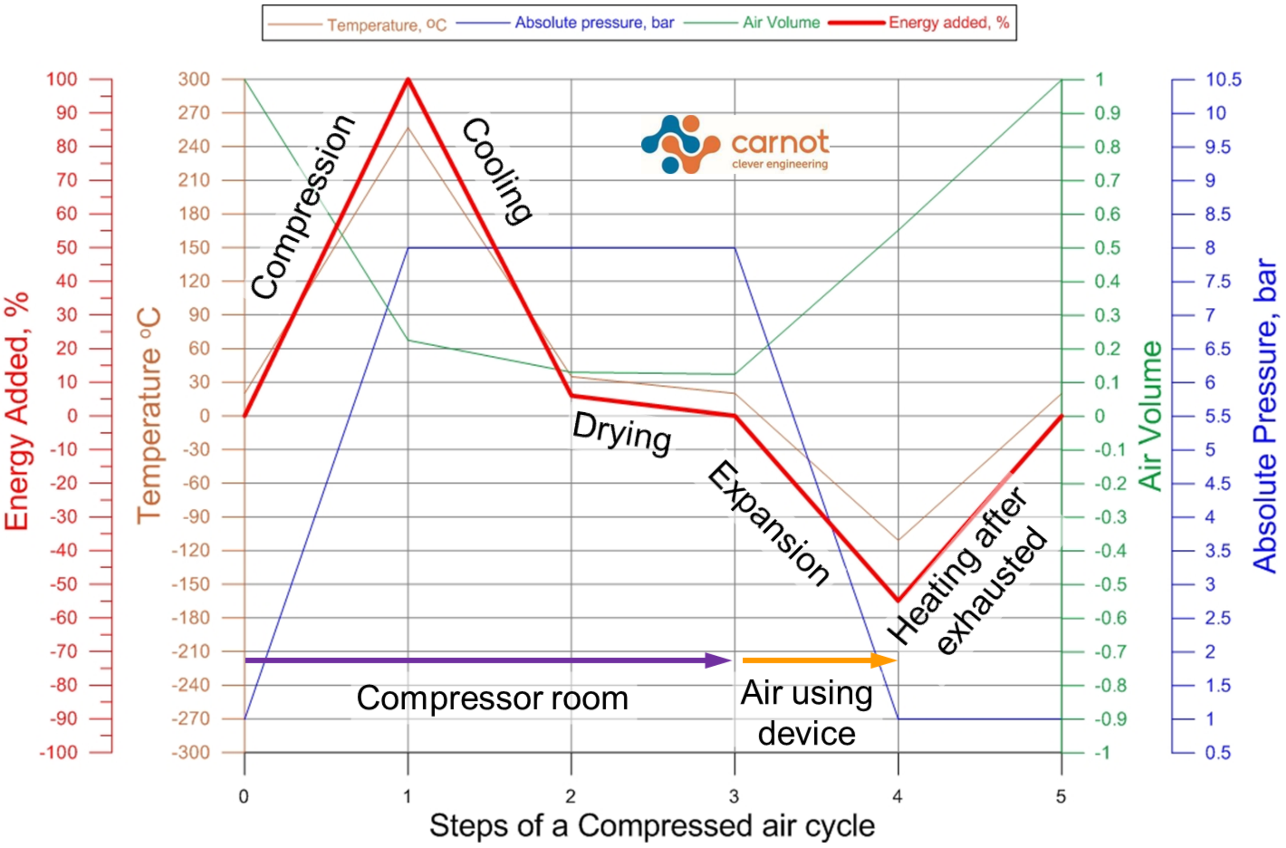

**Figure 2: Steps of a Compressed air cycle in detail**

Figure 2 shows the typical steps in a compressed air cycle for a 7 barg (102 psig) system. These are:

1. The air is compressed to 8 bar absolute (7 barg). The volume of air reduces to 22% of its starting volume. Compressing air by reducing its volume causes both an increase in pressure and temperature. This heat is known as the Heat of Compression. The temperature at the end of compression before losses is 257°C for an inlet temperature of 20°C. The temperature is typical of compressors used for small home duty compressors and is why they burn the paint from their outlet pipes.

   Without allowing for losses, the outlet temperature only depends on the air's absolute temperature entering the compressor and the ratio of the absolute air pressures leaving and entering the compressor.

2. The air is cooled to within 15 degrees of what it was at the compressor inlet. Cooling the air reduces its volume by the ratio of the absolute temperatures.
   This ratio is (20+15 + 273)/(257 +273) = 58 % of what it was before entering the cooler.
   The volume of the air is 12.7 %. Cooling the air rejects 90 % of the energy used to compress it.

3. The air passes through a refrigerated air dryer and leaves it 10 - 15 degrees below the dryer inlet temperature. The air has now been cooled back to about the same temperature as the compressor inlet. Cooling the air has reduced its volume to 55 % of what is when it entered the

cooler. It is now only 12.5 % of the volume it was at the entry to the compressor. A volume of 12.5 % is 1/8th of the inlet volume and consistent with the 8:1 pressure ratio across the compressor.

There is also a slight reduction in volume from water vapour condensed in the coolers and the dryer. The volume reduction can be up to 4 % on a tropical humid day, but in this case, has been ignored.

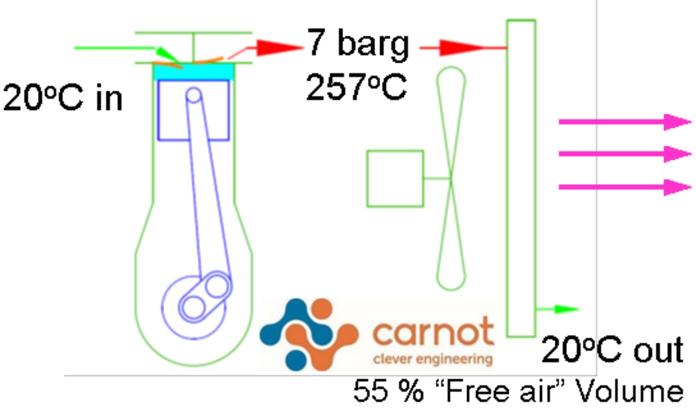

**Figure 3: Simplified graphic of what happens in a compressor room.**

As the air leaves the compressor room despite being at pressure and able to do work, all of the energy used to compress the air is rejected as waste heat.

4. The device using the compressed air expands it (doing work), and if ideal expansion, the opposite of ideal compression occurs. As the volume of air entering the expander is 55 % of what it was leaving the compressor, the most work it can do is 55 % of the work used to compress the air. In a perfect device expanding the air will cool it to a temperature of -111 °C.

5. The air leaving the expander could be heated by cooling a process. If not it will be heated back up to the temperature at the compressor inlet as it mixes with the free air in the factory. This heating causing the volume of the air to expand so that it is the same as it was at the compressor inlet.

This example has used a single-stage piston compressor. A two-stage piston compressor or other types of compressors may use less energy to compress the air to 8 bara. Regardless of the compressor technology used, all of the energy used to compress the air is rejected as heat.

Similarly, different expanders will deliver more energy as work done by the compressed air than others. In all cases, the discharge air will be heated by the "room" air it is exhausting into. The final temperature will be the compressor inlet temperature.

# 3 THE ELECTRICAL - THERMAL ENERGY BALANCE METHOD TO DETERMINE EFFICIENCY

This flawed approach to determining a compressed air system's efficiency doesn't consider the expander's work. It relies on an "energy balance" where the electrical energy supplied to the compressor, less the heat rejected by it, is considered all the energy left in the compressed air and the maximum amount of work it can do. It is common to see claims where 85 % of the energy supplied to the compressor becomes waste heat, leaving only 15 % of the energy left in the compressed air, and this is all the work it can do.

This logic of this method is flawed as:

1. It is not even an efficiency calculation. It is not a ratio of the energy from the expander's work compared to the electrical energy supplied to the compressor.
2. All of the energy supplied to an air compressor is lost as heat. It is just where and at what temperature that varies.
3. We know that compressed air leaving a compressor room even at the same temperature of a compressor room still has pressure and can do work.
4. The value of "85 %" is often used as the amount of heat that can be recovered from an oil-flooded compressor using an OEM heat recovery package. This value of 85% is based only on recovering heat that the compressor oil cooler would reject. It is not a fixed value and does not include the heat from the compressor aftercooler or main and fan motors.

A check of how accurate the electrical - thermal energy balance method is using real world data would show have shown that it is flawed. This has already been done in Section 1 for air motors which for one range of motors had efficiencies from as low as 10 % to as high as 20 %.

Discussions in Section 5 Pneumatic Actuator Efficiency further show that the Electrical - Thermal energy balance method is flawed.

# 4 REAL COMPRESSOR ENERGY FLOWS

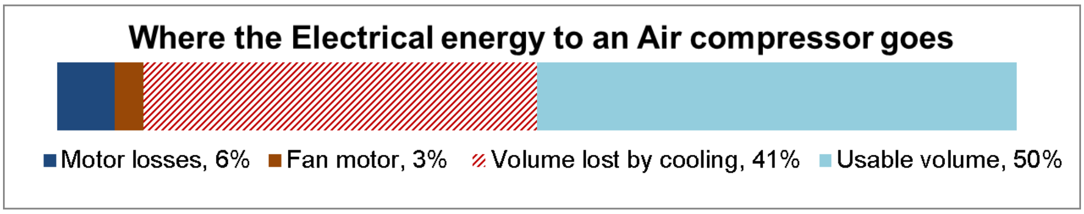

**Figure 4: Where the electrical energy used in an air compressor is rejected as heat.**

In an actual air compressor package, not all of the electrical energy supplied to the package goes into compressing the air to then be rejected as the "Heat Of Compression". There are losses in the main drive motor (3 - 6 %) and the cooling system (fan or pump 2-4 %). For a 7 barg system, the 55 % energy left in the "usable volume" after the aftercooler is part of the 90 – 95 % of the compressor energy input that becomes Heat Of Compression. So the usable energy leaving the compressor is approximately 50 % of the energy supplied to it when loaded.

How much of the electrical energy supplied to a compressor can be recovered as waste heat depends on the compressor technology and the lowest temperature the heat using process needs.

Figure 5 shows that heating water to 60 °C can recover up to 82 % of the heat from a flooded rotary screw compressor if the waters starting temperature was 20 °C.

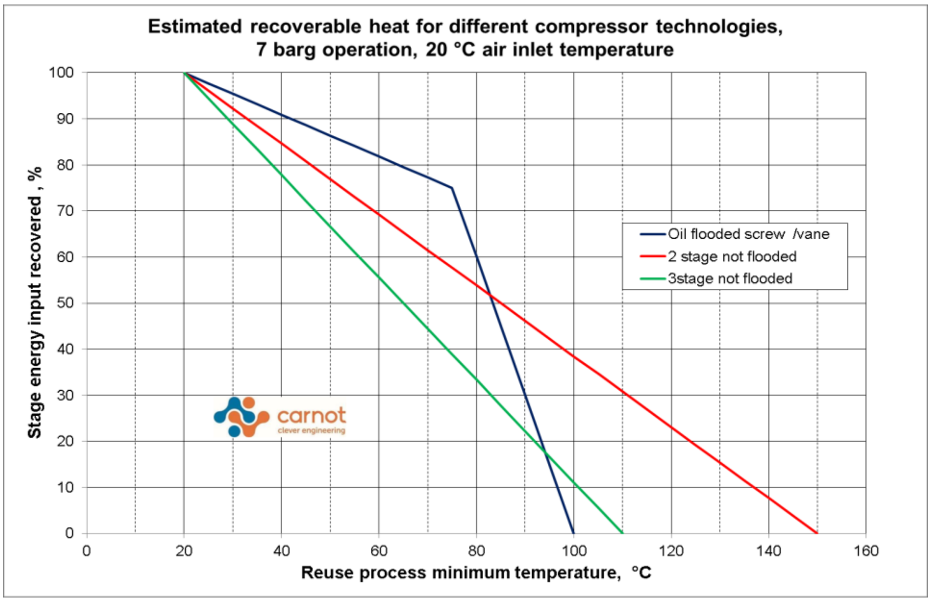

Figure 5: Estimated recoverable compressor heat vs minimum process heat temperature.

This graph only considers Heat Of Compression and does not consider main motor and fan losses. Recovering heat from all of the compressor coolers allows the cooling system to be turned off, saving more energy.

The temperature of the cooling fluid and the humidity of the air being drawn into the compressor affect how much heat is rejected and in which cooler:

- In theory, water-cooled machines often cool the air to below its inlet temperature, which would recover more energy than the electrical energy supplied to the compressor.

- If low humidity air is drawn into the compressor e.g. on very cold or very hot days, often no water condenses in the aftercooler. The aftercooler will reject relatively less heat than other compressor coolers compared to if the intake air had a higher humidity.

Remember that the energy dollars saved by a heat recovery project must be based on the cheapest energy tariff available to the site (e.g. natural gas) not the electricity tariff. Heat recovery will not reduce the cost of operating your air compressors (it may increase it slightly) however it will reduce the overall site energy bill.

# 5 PNEUMATIC ACTUATOR ENERGY EFFICIENCY

The amount of energy used by a pneumatic actuator, e.g. air cylinder, should consider both the extending and retracting movements. The amount of air used by an actuator per stroke is its internal volume x the absolute pressure (bar) in the cylinder immediately before the next stroke. In most actuator applications, the supply air pressure isn't controlled during the stroke, and the pressure in the working side of the cylinder remains "nominally constant".

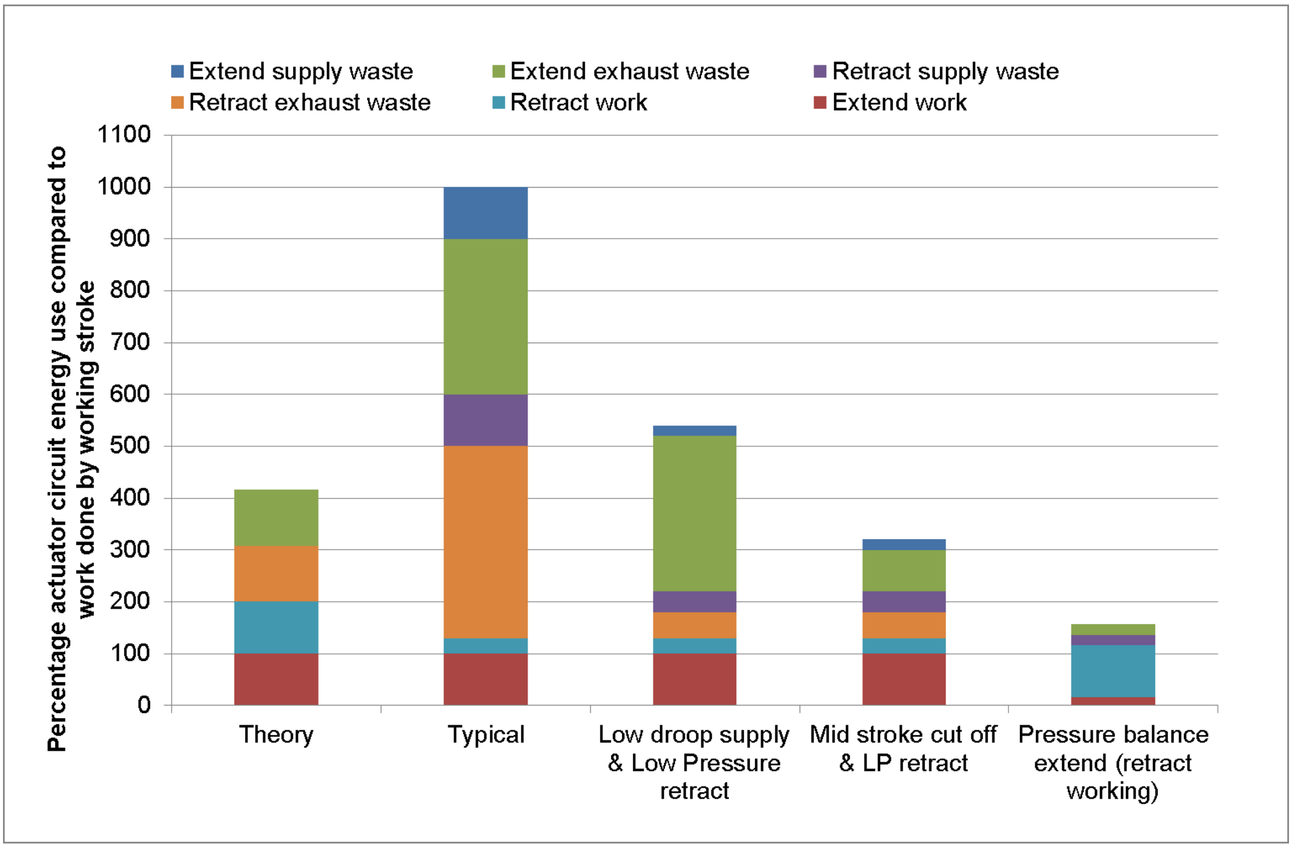

**Figure 6 Pneumatic Air Actuator Energy Use**

Figure 6 shows some examples of how much energy is used for the same amount of work done by the "extend" stroke:

- Pneumatic actuator design theory says for good speed control of the actuator, the actuator should be sized to produce twice the force it needs to. Only half of the pressure does work moving the actuator, the other half does no work but is expanded through the exhaust side parts mostly the speed controller.

  The theoretical circuit then uses 4.17 x the air that it needs to and so is only 24 % efficient. This is 24 % of the possible 55 % of the compressors input power for a conversion efficiency of 13 %
- Typical:
  - Supply pressure drops (droop) cause air to be added to the cylinder after it has stopped. This is more exhaust wastage.

  - For even speed control the non-working end should be at half the pressure applied to the working end. This results in more exhaust wastage and twice as much energy is used than needed.
  - The retract stroke only does work against it own internal friction not the product but uses the same amount of energy as the extend stroke. The work not used is more exhaust wastage.

  This pneumatic circuit has the actuator using 10 times the air that it should for an efficiency of only 10 %. The CAS conversion efficiency for this circuit is 5.5 %

- Low droop supply (minimises supply waste) and Low pressure retract saves Retract exhaust waste. At most two relatively cheap regulators can achieve these savings.
  This circuit uses 5.4 times the air it should for a conversion efficiency of 10 %

- Designing the actuator controls for when in the actuator stroke work is done by using “mid stroke cut off” or variations of “pressure balance” extend can save > 60 % of “typical” air usage. This circuit use 3.2 times what it should for a conversion efficiency of 17 %.

- A more advanced pneumatic design can sometimes use a pressure balance extend where the retract stroke is the working stroke. This circuit is only using 1.57 x the air that it should for a conversion efficiency of 35 %.

As can be seen, the more advanced the controls for a pneumatic actuator the more efficient they can become. Some other methods to improve the efficiency of pneumatics are:

- Reusing air within a machine for a cylinder stroke(s) that can use a lower supply pressure can save up to 85 % in machine air use.
- Expanding the air in multiple steps and heating it from the atmosphere between them can increase the usable volume above 55%.
- The actuator exhaust air can still be used for low pressure blowing and drying provided it is clean enough to do so.

These examples highlight that the efficiency of a compressed air actuator is not constant and that it can be greatly improved with some simple changes.

# 6 OTHER ELECTRICAL POWER USERS ON A COMPRESSED AIR SYSTEM AND SYSTEM ENERGY LOSSES.

There are other electrical power and compressed air users on a compressed air system apart from the devices doing useful work that reduce system efficiency.
These are sometimes used rightly or wrongly applied to distort CAS efficiency values.
As an example it could be said that:

- A compressed air leakage rate of 40 % reduces the usable volume of compressed air from compressor from 50 % to 30 %.
- So the best efficiency an air using device can have is 30 % on a system basis.

This is flawed as any compressed air leak is an air using device in its own right. Yes air leaks are a cost on the compressed air system, but it is an avoidable one

These other power and compressed air users are due to the design, operation and maintenance of the individual systems and can vary greatly. A site can greatly improve the efficiency of their compressed air system by addressing these sources of energy loss:

- Compressor unloaded running power draw and duration
- Leakage. The author has measured site leakage rates from 1-2 % of average air flow to 70 %
- Timed solenoid valve or “thermodynamic” (a type of steam drain) condensate drains. These should be replaced by demand operated no air loss type drains.
- System pressure drops
- Compressed air dryers

  The power draw of a refrigerated air dryer correctly derated for hot (e.g. 40°C) conditions will be approximately 4 % of the compressor plant installed power. The dryers must be sized to handle all of the installed compressor capacity. For most refrigerated air dryers (with a Hot Gas Bypass Valve) the power draw is constant regardless of compressed air flow or temperature. A power draw of 4 % of compressor plant installed power becomes 10 % of operating compressor power draw at a 40 % air flow.
  More efficient dryers designs e.g. cycling thermal mass types vary their power draw with cooling load. In 40°C conditions for a 40 % air flow they would only use 4 % of the operating compressor power. In 25°C conditions they would only use 2 %.

  Desiccant dryers can use even more power (15-30 % of installed compressor power) and should always be fitted with dewpoint dependent controls to minimise energy waste.

# 7 CONCLUSION

This article has described the energy flows in a compressed air system (CAS). This was done to better inform discussions about CAS EE work and how to properly calculate energy savings. The article has also provided a discussion about the correct way to calculate efficiency of a CAS and provided some examples of how advanced pneumatics and reduce the energy used pneumatic actuators.

In doing so the article has:

- Highlighted the flaws of only considering the compressor room equipment and not the expanders efficiency when calculating CAS efficiency.
- Shown some examples of how advanced pneumatics can improve a pneumatic actuator’s efficiency by reducing how much air it uses to achieve its task.
- Discussed other energy users in a compressor room and common sources of air and energy waste.

This article should guide those calculating the economics of compressed air energy efficiency projects away from using potentially fraudulent “rules of thumb” to seeking out and collecting well-informed data. This data will ensure that future projects are supported by sound economics.

For help with improving the efficiency of your compressed air system or wider site energy services contact the author at mnottle@carnot.com.au or visit www.carnot.com.au.