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Environmental Sustainable Pneumatics

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Abstract.

Environmental sustainability has become a key priority in production and manufacturing engineering, driven by increasing regulatory requirements and customer expectations for reduced environmental impact. Of course, this is also due to the realization that the current economic model cannot be continued for ecological reasons. The transition to climate-neutral and resource-efficient production creates high pressure to adapt to pneumatics. After all the problem lies in the high energy demand (compared to electric drives) and the associated high CO_2 emissions. The assumption that customers switching to green electricity will solve the problem could be too short-sighted.

The focus of this paper is on drive technology, other areas such as vacuum technology are only dealt with in passing. After an introduction including a summary of the European Ecodesign for Sustainable Products Regulation (ESPR) [1] in chapter 1, chapter 2 deals with the possibilities for improving the energy efficiency of pneumatic actuators, including compressed air generation and distribution, as the greatest challenge with regard to CO_2 neutrality. Chapter 3 describes the Product Carbon Footprint (PCF) of pneumatic components, i.e. the CO_2 emissions caused during their production. An initial assessment with regard to the circular economy is provided in chapter 4. Finally, the topics mentioned are summarized in chapter 5 in the form of a comparison between pneumatic and electric drive technology.

1. INTRODUCTION

The German Federal Environment Agency [2] defines six principles that can be used to determine eco-design – and which can therefore be used as a benchmark for environmental sustainable pneumatics. These are

- **Durability**
  An area in which pneumatics has significant strengths due to its reliability and robustness.
- **Repairability**
  Repair kits for pneumatic actuators have been offered for decades. Due to the modularity of their design, maintenance units and valve terminals also have the option of replacing

a defective module, e.g. a valve. In this way, the entire system, in our example the valve terminal, is quickly put back into operation.

- **Resource efficiency**
  This aims to reduce the consumption of energy, materials and water in the production process and during the product life cycle. Behind the water consumption during the use phase but also in the production of pneumatic components, a tick can be set very quickly. The material consumption of pneumatics is also comparatively low, as described in chapter 3 on the Product Carbon Footprint cradle to gate (PCF ctg). Energy consumption, on the other hand, is the central challenge, which is dealt with in detail in chapter 2.
- **Lack of problematic substances**
  In pneumatics, this is usually the case, apart from lead in piezo valves or using of per- and polyfluoroalkyl substances (PFAS) [3]. The last ones are depending on the application used in seals and lubricants [4, 5], partly also in other plastic components.
- **Renewable raw material**
  are hardly used in pneumatics. The majority of pneumatic components consist of aluminum and steel, both of which can be easily and economically recycled (see chapter 4.4). There is potential for further development with regard to renewable raw materials in the field of seals and lubricating greases. Of course, tubes, valve housings, sensor housings or various cover plates made of plastic based on renewable raw materials are also a possibility.
- **Circular Economy (CE)**
  Due to their simple design and robustness, pneumatic components are well suited for the CE-strategies RePair and ReUse as well as ReCycling (see chapter 4). The ReFurbish and ReManufacture strategies, on the other hand, are hardly used at the moment, so they are a future option.

In the following subchapters, important aspects of ‘Environmental Sustainable Pneumatics’ are discussed. These are energy efficiency (chapter 2), Product Carbon Footprint (chapter 3) and Circular Economy (chapter 4). Chapter 5 summarizes the results.

2. ENERGY EFFICIENCY

Energy efficiency has been a topic in pneumatics for many years. And numerous publications have been published on this subject, including some with an overview character [6, 7, 8].

The energy transition from fossil fuels to CO_2-neutral energy sources requires significant improvements in the energy consumption of pneumatic systems. This is because the demand for electrical energy is increasing significantly as a result of the energy transition – whether for the operation of cars (electromobility), for heating buildings (heat pumps) or for hydrogen generation (electrolyser). In these and many other cases, electricity is needed. Accordingly, (green) electrical energy is and remains a rare resource that should only be used efficiently in the future. For pneumatic applications, this also results in the need for efficiency, as electrical energy is used to generate compressed air (see chapter 2.1). To illustrate the need for energy-efficient pneumatics with a concrete example, reference can be made from the sustainability report of Festo from 2024 [9].

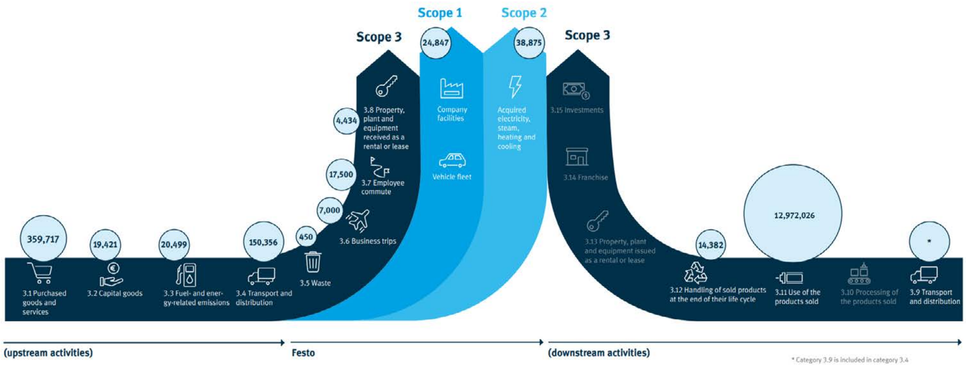


Figure 1. Company Carbon Footprint (CCF) 2024 of Festo [9]

The report shows the Company Carbon Footprint (CCF) of Festo, see Figure 1. 95% of the CCF of Festo is caused by Scope 3.11, the ‘use of product sold’. Festo also sells components such as electric actuators, sensors, valves, valve terminals, ... that have a direct electrical energy consumption. But the ‘indirect’ electrical energy consumption for compressed air generation is by far the largest part of Scope 3.11. About half of the remaining 5% of the CCF is Scope 3.1, the CO_2equivalent (CO_2e) of the ‘purchased goods and services’. The next largest share of just under 1% of the CCF is caused by the delivery of supplier or (own) preliminary products to our factories (Scope 3.4, ‘transport and distribution’). Both factors are well described by the aggregation of the PCF ctg of the products sold (see chapter 3).

Festo has set itself the goal of reducing greenhouse gas emissions in Scope 3 by 90 per cent by 2050 compared to the base year 2022 [10]. This ambitious climate target was officially validated by the Science Based Targets initiative (SBTi) in February 2025. In the Target Dashboard of the SBTi [11] not only Festo can be found. It reads a bit like the ‘Who's Who’ of the pneumatics industry and its suppliers: SMC Corporation, Emerson Electric Co. (Aventics), IMI plc. (Norgren), Parker Hannifin Corporation, Schunk SE & Co. KG, Trelleborg AB, ... This demonstrates the importance of CO_2-reduction for the pneumatic industry and their customers, which are also widely represented there.

In the following subchapters, the entire compressed air chain is described from an energy perspective, from compressed air generation (chapter 2.1) to its distribution (chapter 2.2) to the operation of machines and systems (chapter 2.3). Chapter 2.4 concludes the topic of energy efficiency with the control of pneumatic actuators.

2.1. Compressed air generation

Pneumatic energy efficiency starts with the compressor. Since thermodynamic effects inevitably generate a lot of heat during the compression and generation of compressed air [12], and this cannot be used pneumatically, compressor manufacturers are very concerned with the topic of heat recovery [13, 14, 15]. The recovered heat can be used, for example, for heating purposes or to generate required process heat. There are also solutions to heat rooms with the compressors in winter and to cool them in summer by means of absorption chillers [16].

In summary, future improvements in compressor technology to recover heat and reduce specific power consumption for air compression [6] will help pneumatics reduce their CO_2 emissions in Scope 3.11.

In the future, it may become a niche application that compressed air is no longer generated centrally via large compressor stations, but decentral on site. Initial solutions for a decentral pressure supply, e.g. for pneumatic grippers, are already available on the market [17, 18]. Decentralized compressors for vacuum generation for suction cups are also offered on the market for several years [19, 20].

2.2. *Compressed air distribution*

After generation, the compressed air is distributed in smaller or larger compressed air networks. These must be appropriately dimensioned and designed with a view to the connected loads. To avoid losses due to leaks, regular inspection and monitoring of the compressed air network is helpful. Accordingly, there are various providers – from start-ups to pneumatics suppliers – that are active in this area [21, 22]. Comparable offers are also available from compressor manufacturers [23]. The monitoring of the compressed air network is also partly linked to a management system that determines the most efficient combination of compressors supplying the compressed air network for the current compressed air consumption [24]. Acoustic cameras from various manufacturers have proven to be a practical tool for easy detection of the exact location of the leak [25, 26].

2.3. *Design and operation of machines and systems*

The basics for efficient design and efficient operation of pneumatic systems in machines and plants are known for a long time. As an example, a white paper by Festo from 2013 describes basic approaches to reducing compressed air consumption [27], cf. Figure 2.

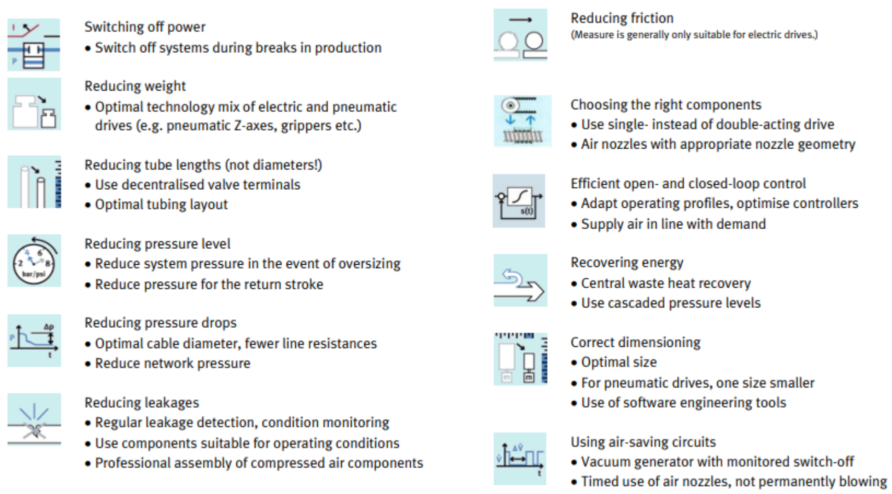
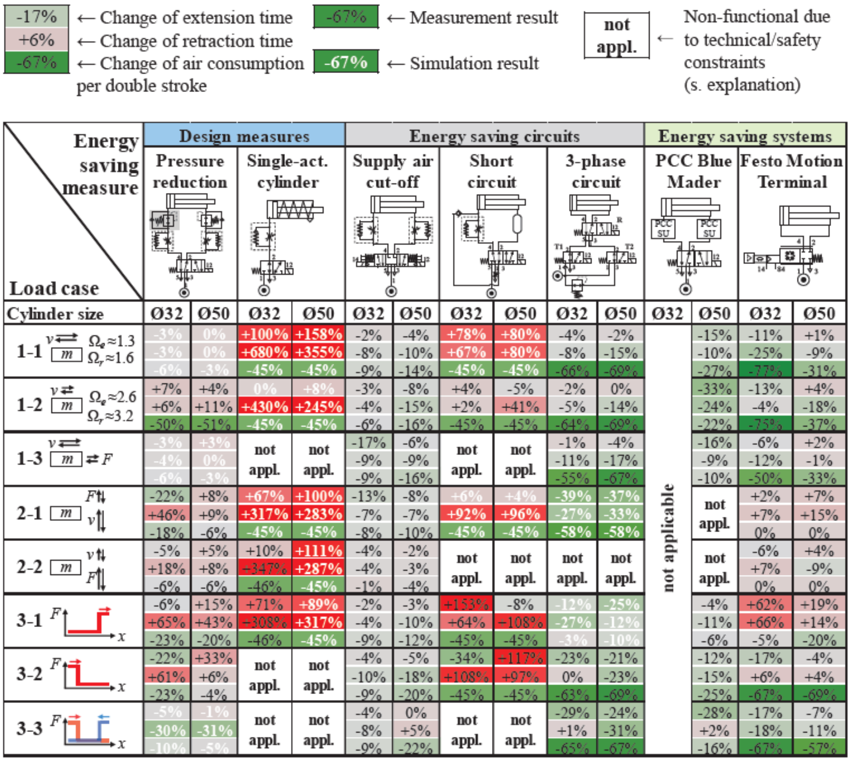


Figure 2. Measures to reduce compressed air consumption [27]

As well as for the compressors and the compressed air network, there are now also solutions for monitoring individual machines and systems. One example is the SFAM flow sensor with integrated pressure sensor from Festo, which can be used to detect compressed air fluctuations, leaks and other anomalies as part of a maintenance unit [28]. In addition, there are also monitoring systems that enable compressed air shutdown or pressure reduction in the event of detected downtimes of the machine/system [29, 30]. E²PME, a start-up from Marly (CH), goes one step further. They offer a data logger that can be used to record and evaluate the pneumatic and electrical power consumption of a machine. In the event of a standstill, electrical circuits can be switched off in addition to the compressed air, which, according to E²PME, allows savings of between 25 and 50 % in stand-by mode [31].

2.4. Pneumatic drive technology and its control

For the individual drive, the correct design and dimensioning is first of all necessary, as made possible e.g. by the web tool pneumatic simulation from Festo [32]. This is based on the Pneumatic Frequency Ratio (PFR), which describes the relationship between the pneumatic natural frequency and the application-specific frequency [33].



Energy saving measure / Load case	Design measures: Pressure reduction		Design measures: Single-act. cylinder		Energy saving circuits: Supply air cut-off		Energy saving circuits: Short circuit		Energy saving circuits: 3-phase circuit		Energy saving systems: PCC Blue Mader		Energy saving systems: Festo Motion Terminal	
Cylinder size	Ø32	Ø50	Ø32	Ø50	Ø32	Ø50	Ø32	Ø50	Ø32	Ø50	Ø32	Ø50	Ø32	Ø50
1-1 $\Omega_e \approx 1.3$ $\Omega_r \approx 1.6$	-3% -3% -6%	0% 0% -3%	+100% +680% -45%	+158% +355% -45%	-2% -8% -9%	-4% -10% -14%	+78% +67% -45%	+80% +80% -45%	-4% -8% -66%	-2% -15% -69%	not applicable	-15% -10% -27%	-11% -25% -77%	+1% -9% -31%
1-2 $\Omega_e \approx 2.6$ $\Omega_r \approx 3.2$	+7% +6% -50%	+4% +11% -51%	0% +430% -45%	+8% +245% -45%	-3% -4% -6%	-8% -15% -16%	+4% +2% -45%	-5% +41% -45%	-2% -5% -64%	0% -14% -69%		-33% -24% -22%	-13% -4% -75%	+4% -18% -37%
1-3	-3% -4% -6%	+3% 0% -3%	not appl.	not appl.	-17% -9% -9%	-6% -9% -16%	not appl.	not appl.	-1% -11% -55%	-4% -17% -67%		-16% -9% -10%	-6% -12% -50%	+2% -1% -33%
2-1	-22% +46% -18%	+8% +9% -6%	+67% +317% -45%	+100% +283% -45%	-13% -7% -8%	-8% -7% -10%	+6% +92% -45%	+4% +96% -45%	-39% -27% -58%	-37% -33% -58%		not appl.	+2% +7% 0%	+7% +15% 0%
2-2	-5% +18% -6%	+5% +8% -6%	+10% +347% -46%	+111% +287% -45%	-4% -4% -1%	-2% -3% -4%	not appl.	not appl.	not appl.	not appl.		not appl.	-6% +7% 0%	+4% -9% 0%
3-1	-6% +65% -23%	+15% +43% -20%	+71% +308% -46%	+89% +317% -45%	-2% -4% -9%	-3% -10% -12%	+153% +64% -45%	-8% +108% -45%	-12% -27% -3%	-25% -12% -10%		-4% -11% -6%	+62% +66% -5%	+19% +14% -20%
3-2	-22% +61% -23%	+33% +6% -4%	not appl.	not appl.	-4% -10% -9%	-5% -18% -20%	-34% +108% -45%	+117% +97% -45%	-23% 0% -63%	-21% -23% -69%		-12% -15% -25%	-17% +6% -67%	-4% +4% -69%
3-3	-5% -30% -10%	-1% -31% -5%	not appl.	not appl.	-4% -8% -9%	0% +5% -22%	not appl.	not appl.	-29% +1% -65%	-24% -31% -67%		-28% +2% -16%	-17% -18% -67%	-7% -11% -57%

Figure 3. Change in performance and air consumption of energy-saving circuits in comparison to the standard meter-out circuit [34]

The PFR is also discussed in a recent publication in the Journal for Fluid Power [34] by comparing control strategies for pneumatic drives with regard to energy consumption and cycle time for different, typical applications (see Figure 3). As this publication shows, the supply air cut-off offers a way to save up to 20% of energy and time compared to pneumatic meter-out circuit in a wide range of applications. Instead of a 5/2-way valve, this control technology uses a 5/3-way valve with a closed center position, which is switched to the middle position when the end position is reached. As a result, the drive chamber is no longer filled with compressed air. The final pressure in the end position remains low, which saves energy. This has the additional effect that less pressure needs to be exhausted to start the countermovement. Thus, cycle time is shortened. If energy efficiency becomes more important, such a solution may get a stronger footprint in the market.

As can be seen in the right part of Figure 3, more complex energy saving systems are required to achieve greater savings. One example for such a solution is the Motion Terminal VTEM of Festo with the ECO drive app, which is operated at the minimum required pressure depending on the load [35]. At the end of the movement, there is therefore no further increase in pressure in the drive chamber – comparable to the supply air cut-off.

Another example of an energy-saving system is Smart Switching Lite, which is available on the new valve terminal VTUX from Festo [36]. This uses a 5/4-way valve that has two center positions (see Figure 4). In these, the air supply to the ventilation chamber is interrupted, while the ventilation path remains open. This means that no further compressed air is consumed after switching in one of these two middle positions. In principle, as with the supply air cut-off described above, the pressure build-up is stopped – only earlier, during movement and not only when the end position is reached. Accordingly, the pressure in the drive chamber is even lower in the end position – and even less pressure has to be released after the countermovement has been initiated. This further reduces the cycle time.

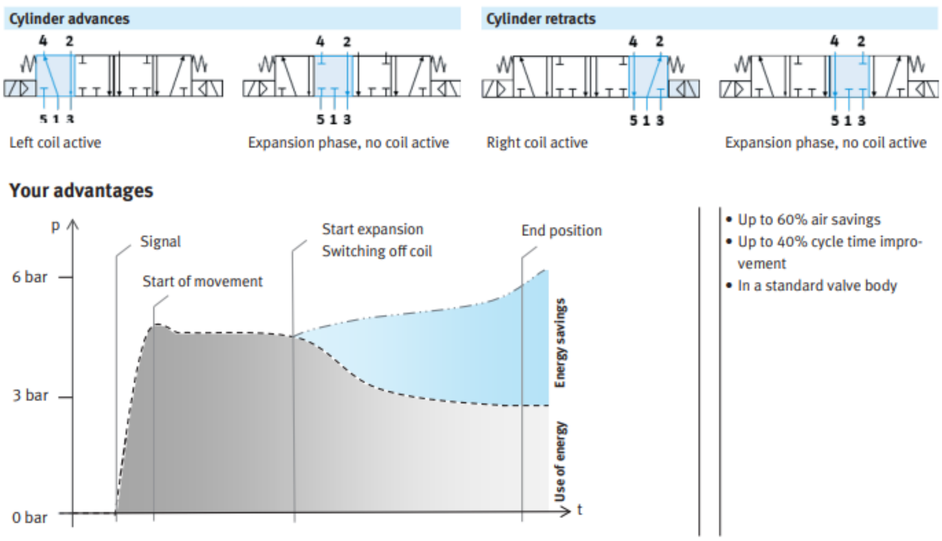


Figure 4. How Smart Switching Lite works [36]

The ECO drive with the Motion Terminal VTEM and Smart Switching Lite on valve terminal VTUX are two examples of what Festo calls Controlled Pneumatics [37]. This describes solutions in which, in contrast to today's common switching pneumatics, control of one or more state variables are possible. This also includes, but is not limited to, servo pneumatics, i.e. the position control of cylinders. Pressure or flow control are also part of Controlled Pneumatics.

In the field of pneumatic vacuum generation, energy savings are made possible by solutions that integrate the ejector itself as well as valve technology to control the supply air and sensors. Such vacuum generator systems reduce the amount of air required to achieve a target vacuum to a minimum. In this way, air-saving functions and functions for energy and process control are possible [38, 39].

3. PRODUCT CARBON FOOTPRINT (PCF)

For a complete CO_2 comparison of different drive solutions, not only the energy consumption in operation and the associated CO_2 consumption is important, but also a ‘starting value’ is required for the comparison. This is because without the drive having carried out a single stroke, energy has already been consumed to generate the components used, thus CO_2 emissions were generated.

According to the Greenhouse Gas Protocol (GHG) [40], a distinction is made between a Product Carbon Footprint cradle-to-gate (PCF ctg) and cradle-to-grave. PCF ctg is ‘a partial life cycle inventory, including all emissions and removals from material acquisition through to when the intermediate product leaves the reporting company’s gate’. Cradle-to-grave also includes the use phase of the product (see chapter 2) and the emissions at the end of the life cycle. In the following, PCF is always understood to be PCF ctg. This is because it offers the required ‘starting value’ for a CO_2-comparison of different drive solutions, comparable to the historical costs [41] in a total cost of ownership (TCO) analysis [42].

The methods for determining this PCF ctg are described theoretically, for example in EN ISO 14067 [43] or the VDMA Guideline ‘Calculation of the Product Carbon Footprint in Mechanical and Plant Engineering’ [44]. In practice, however, there are some challenges, following is an example:

A pneumatic and an electric drive solution are to be compared with each other for a specific application. On the pneumatic side, all components must be taken into account, from the air preparation unit, covering the fittings and tubes, the valve terminal up to the throttle and cylinder. And these components must be included into the comparison in the right configuration, for example the cylinder with the correct diameter and stroke, the selected end position damping, the desired piston rod shape, ...
In the case of air preparation units and valve terminals, only the proportion required for the individual drive should be considered. The ratio to be taken into account must be calculated even smaller if several drives are supplied with compressed air via one valve – as is usually, for example, in the control of clamps in the body shop of the automotive industry.

It is therefore necessary to provide customers with good support in the design tools in order to be able to compare systems appropriately with each other. In any case, the quality of the data taken into account to determine the PCF ctg must be declared. This is because one pneumatic supplier only calculates the PCF ctg approximately, the other puts a lot of effort into it. The difference between the two approaches can only be made clear to the customer by information on data quality. Concerning the question how to calculate the data quality of subsystems or even entire drive solutions by using the data quality of individual components or parts, it may be necessary to refine the regulation.

Further refinement of the regulatory framework is required, how PCF ctg calculations can be compared with each other in a simple and clear manner – from individual components to subassemblies to complex systems. This is because a major advantage of pneumatics lies in its low investment costs. Can it really be assumed that a customer will place the extensive documentation of different suppliers next to each other for each of the large number of cost-effective components? And compare them in detail? The 'Example presentation PCF reporting' in the VDMA Guideline [44] comprises 5 pages – unfilled.

The low investment costs of pneumatics correlate with a low PCF ctg. This is because pneumatic components for a drive solution are much more compact and have a lower mass than comparable electric drive solutions. This reduces both the material required in production and the energy required during production, for example when using machinery. The lower PCF ctg of pneumatic compared to electric drive technology can also have a monetary effect. This is because the aggregation of the material share of the PCF of all products sold should result in Scope 3.1 ('purchased goods and services', see chapter 2) of the CCF. As SBTi allows to compensate emissions from the CCF under certain conditions – i.e. certificates from climate protection projects for CO_2-sinks [cf. 45] – a low PCF and CCF also become relevant from an economic perspective. It should be noted, however, that CO_2-compensation is only permitted as a supplementary measure for unavoidable residual emissions that are subject to strict quality requirements [46, 47].

The Carbon Border Adjustment Mechanism (CBAM) [48] is the EU's tool to set a fair price for CO_2-emissions from the production of carbon-intensive goods imported into the EU and to promote cleaner industrial production in non-EU countries. In the medium term, this could have the effect that low CO_2-equivalents of materials and the products produced from them also become economically cheaper.

4. CIRCULAR ECONOMY (CE)

Circular economy (CE) is a 'is a model of resource production and consumption that involves sharing, leasing, reusing, repairing, refurbishing, and recycling materials and products, to extend product life cycle for as long as possible' [49]. In the meantime, with ISO 59000 [50] there exists a family of standards concerning CE. And CE has found its way into legislation. In line with the EU's 2050 climate neutrality goal under the Green Deal, the European Commission proposed in March 2022 the first package of measures to speed up the transition towards a CE, as announced in the Circular Economy Action Plan [51, 52]. CE is also part of the Ecodesign for Sustainable Products Regulation (ESPR), which entered into force in 2024 [53, 54]. As Figure 5 shows, ecodesign requirements such as durability and reliability are described there, in which pneumatics has strengths.

(a) durability;
(b) reliability;
(c) reusability;
(d) upgradability;
(e) repairability;
(f) the possibility of maintenance and refurbishment;
(g) the presence of substances of concern;
(h) energy use and energy efficiency;
(i) water use and water efficiency;
(j) resource use and resource efficiency;
(k) recycled content;
(l) the possibility of remanufacturing;
(m) recyclability;
(n) the possibility of the recovery of materials;
(o) environmental impacts, including carbon footprint and environmental footprint;
(p) expected generation of waste.

Figure 5. Ecodesign Requirements, ESPR Article 5.1 [53]

Other requirements, such as energy and resource efficiency, have already been described in chapters 2 and 3. Requirements such as repairability and recyclability are directly linked to the CE.

In our view, the most important CE-strategies for pneumatics as presented in Figure 6 are ReUse (chapter 4.1), RePair (chapter 4.2), ReFurbish and ReManufacture (chapter 4.4) as well as ReCycle (chapter 4.4) as final step. They will be discussed in the mentioned chapters under perspective of pneumatics. To define the mentioned Re-Strategies, reference is made to ISO 59004 [55], which describes the 'vocabulary' of CE (see Table 1).

One challenge to realize CE in the field of pneumatics can be described using the example of seals. DIN 7716 describes the requirements for the storage of rubber and rubber products [56]. According to this, care must be taken 'to ensure that the products are stored stress-free, i.e. without tension, pressure or other deformations'. However, this is not the case in the installed state of seals. If, for example, for a cylinder or a valve the Re-Strategy ReUse should be used, there may be a significant time interval between the first and the second use. But how long can this be? A week, a month, a year? Or even several? With ReFurbish, too, the question arises, whether seals must be replaced in principle. Or is the sealing still in such a good condition that it can be used in the refurbished component without any significant risk? For lubricating greases, bearings and guides or electronic components [57], there are comparable challenges.

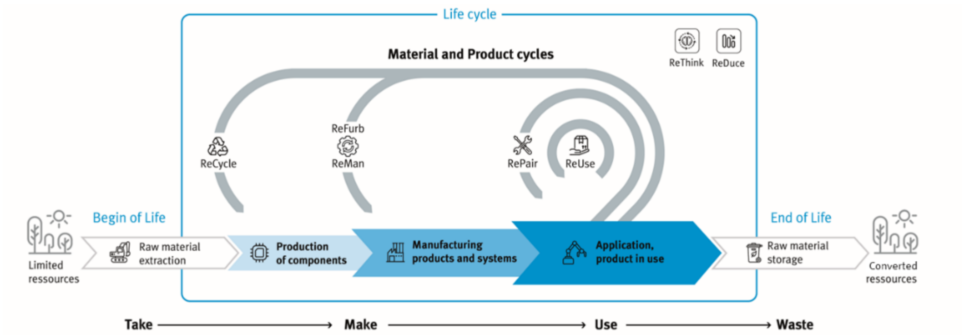


Figure 6. Re-Strategies of the CE

Table 1 – Definition of Re-Strategies in ISO 59004:2024 [55]

Action	Description
RePair	action to restore a product to a condition needed for the product to function according to its original purpose.
ReUse	use of a product or its component parts after their initial use, for the same purpose for which they were originally designed
ReFurbish	restore an item, during its expected service life, to a useful condition for the same purpose with at least similar quality and performance characteristics
ReManufacture	return an item to original condition from both a quality and performance perspective using an industrial process
ReCycle	activities to obtain recovered resources or use in a process or a product, excluding energy recovery

In order to decide on the selection of a suitable Re-Strategy at the end of the first service life, a large amount of information about the component is therefore necessary. In the Factory-X project [58], a proposal for structured data storage (cf. Figure 7) was created for this procedure, called R-Grading. This makes clear that the trends of CE and digitization must be considered together. Moreover, a Digital Twin offers the opportunity to securely and consistent store the large amount of data required over the long service life of the many components, so that a robust decision for a Re-Strategy can be made on this basis.

General Information	Operational Data	History	Physical State
Operator Location	**Environment** • Temperature • Humidity • UV radiation	**Crash Incidence** • Emergency shutdowns • Crash time	**Component operational/functional**
Date of Installation	**Operating time** • Processing Time • Down Time • Operation Time	**Maintenance Operations**	**Technical State**
Expected Wear	**Sensor Data and time series** • Pressure Level • Operating Voltage	**RePair Operations**	**Optical State**
Installation Location	**Compressed Air Quality**	**ReFurb/ReMan Operations**	
	Load and stress	**Number of power on/off cycle**	
		Predictive Maintenance, Condition Monitoring **Singular Events** • Pressure too low • Pressure spikes • Voltage to low • Voltage spikes **Gradual Changes** • Leakage • Friction	

Figure 7. Structure to implement CE-relevant data in an Asset Administration Shell

4.1. RePair

The repair of pneumatic components has a long tradition. The high robustness and reliability of pneumatic components as well as the simple design of the components are certainly reasons for this. Because under these conditions, a repair is worth it, i.e. the replacement of seals or the re-greasing of the components. Spare parts for this are available from Festo, for example, via a spare-part catalog [59], as well as videos to help with the repair [60]. Even tools and repair equipment are available [61].

All the examples mentioned aiming to ensure that the end customer's maintenance staff can repair the pneumatic components on its own. To send back components to the manufacturer for repair is currently not very common in pneumatic drive technology – in contrast to electric drive technology.

As shown in Table 1, there is a definition for RePair according to ISO 59004:2004 [55] ‘restore a product to a condition needed for the product to function according to its original purpose’ But what does this mean in practice? There is a distinction between regenerative repair, i.e. the restore and further use of defective parts or components, and replacement repair, i.e. the replacement of worn or defective components with new components [62]. Replacement repair is probably most common for pneumatic components. This is because a machine/system is repaired by, for example, replacing a defective valve terminal. This is quick and makes it possible for the production plant not to come to a standstill or to restart quickly. The removed valve terminal is repaired, e.g. by replacing a defective valve or another defective module. The valve is repaired by changing the pilot valve, for example. The pilot valve ...
The way in which the repair of pneumatic components will become established and at which of the levels mentioned must and will be tested on the market.

4.2. ReUse

There is probably a long history in the field of ReUse of pneumatic components, even if this is usually not transparent for the manufacturers of pneumatic components. What stops a user from utilizing a valve terminal, a maintenance unit, a pneumatic actuator or even more complex systems such as hall and robot installation platforms (see Figure 8) [63] in the next machine/system when the original machine/system is demounted?

In some cases, the end user is even actively supported in ReUse. For valve terminals and maintenance units, for example, Festo offers a modification aid that supports reconfiguration and thus, reduces the effort required for ReUse [64].

What happens if a machine/system is to be taken out of service and then will be demounted? At latest, the contracted waste disposal company will take a close look at the entire structure and demount valuable components for which it sees a market and ReUse them separately from the remaining parts. It seems, that this is already happening today, because you can find used pneumatic components on various internet portals [65, 66].

In order to increase the ratio of reused components, it would be helpful in future if the component itself – for example via a Digital Twin – provides information about its current ‘state of health’ and how much of its statistical lifespan it already has consumed. The technical terms on this in the course of the CE are ‘Health Management’ and ‘Remaining Useful Life’ (RUL) [67]. This requires access to the data mentioned in Figure 7.

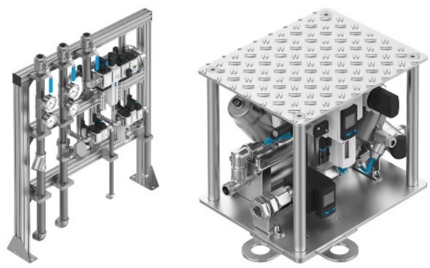


Figure 8. Examples for Hall and Robot Plates (HIP, RIP) [63]

4.3. ReFurbish and ReManufacture

According to the definition of ISO 59004:2004 [55, see Table 1], the take-back/repurchase of components and systems, their reconditioning in different quality levels and the ultimately resale is referred to as ReFurbish and ReManufacture.

While there is a wide range of options for reconditioning motors and motor controllers for electric drives and drive systems [68, 69, 70], this is still largely unknown in pneumatics. The customers of pneumatics, i.e. the machine builders, are already one step ahead. For example, there are offers with integrated pneumatics for rebuild machines [71], pre owned machines [72] or used machines [73]. The general labels for these different terms are ReFurbish and ReManufacture.

Just as with ReUse (see chapter 4.2), Digital Twins are helpful for realizing ReFurbish and ReManufacture for components. This is because the manufacturer of the component needs information about the usage history of the specific product in order to set a buyback price. How intensive was the use? Under what environmental conditions was it used? Has maintenance and servicing been carried out? If so, how? This and other information (see Figure 7) must be provided by the owner of the component so that the manufacturer of the component is willing to pay a higher price than the scrap price. Only by sharing data an economic benefit for all partners involved can be derived from ReFurbish or ReManufacture.

A specific challenge of pneumatics is that only limited data is available. With this little data, you can certainly achieve important insights in the sense of predictive maintenance [cf. 74]. But since far more data is available for electric drives, more or more accurate information can be derived from it. This fact could result in a disadvantage for pneumatics in the future with regard to ReFurbish and ReManufacture. In the end, it leads to the question already mentioned in the introduction to chapter 4, with which data should a Digital Twin be filled? Fortunately, there are currently some research projects related to fluid power technology such as Factory-X [58], Fluid 4.0 [75] or CliCE-DiPP [76], which deals with the development of Digital Twins based on the Asset Administration Shell (AAS).

For pneumatic components and systems, this raises the question of which of the large number of products a ReFurbish and/or ReManufacture makes sense from an economic as well as an ecological perspective? This is because the deployment, operation and maintenance of a Digital Twin are associated with costs and CO_2e. Even the return transport from the owner/user to the manufacturer cannot be achieved without economic and ecological costs. This significantly limits the number of pneumatic components for which a corresponding offer makes sense.

To put it another way: For typical C-parts such as screws, nuts or washers [77] a ReFurbish or ReManufacture probably doesn't make sense, so not for a Digital Twin. But there is obviously a market for used machines, otherwise there would be no corresponding offers. And somewhere between these two extremes, there is a borderline at which a Digital Twin and the associated CE offerings become ecologically and economically useful.

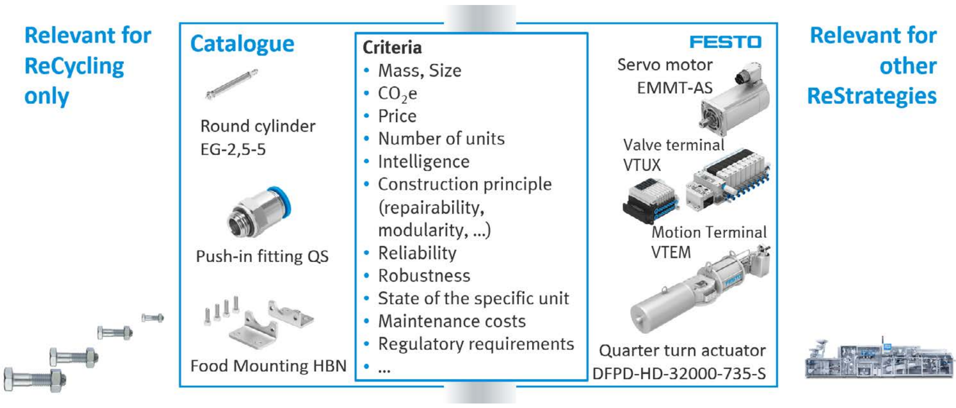


Figure 9. Possible criteria for deciding whether a Digital Twin and the services based on it make sense for CE

This borderline probably runs directly through the catalog of pneumatics suppliers as Festo. To make it concrete with the example of a pneumatic cylinder. Festo offers cylinders with piston diameters from 2.5 mm to 735 mm [78, 79], the product weight for these pneumatic cylinders varies from 2 g to 1.5 kg. It is therefore obvious that the same Re-Strategy does not make sense for all pneumatic cylinders. Figure 9 shows some possibilities for criteria that can be used to draw the mentioned borderline.

4.4. ReCycle

In terms of their mass and very roughly considered, pneumatic components consist of a lot of aluminium, some plastic (in a wide variety of variants) and steel (see the distribution of production materials of Festo [9] shown in Figure 10). In addition, there are some other materials in smaller quantities, e.g. copper, zinc and brass.

For the aluminium production bauxite is needed, which has been declared in the European Union since 2020 as a Critical Raw Material [80]. According to the fifth list of EU critical materials [81], which was published in 2023, aluminium itself is also classified as a Critical Raw material [82, cf. also 83].

Aluminium can be easily recycled as a high-quality metal. The End-of-Life Recycling Rate (EoL RR, [84]) was 69% in Europe in 2021 [85]. Iron and thus steel has an even higher EoL RR, which was already 75% in 2015 [85]. The recycling of plastics is much more complex. For further details, please refer to [86]. With regard to pneumatic components, it should also be mentioned that there are initial considerations to ReCycle sealings [87].

Due to the simplicity of the design of pneumatic components, only a limited number of raw materials are required. On the electronic circuit of a motor controller as example, many more components and raw materials (including critical ones) are used. The recycling processes for electric components are correspondingly more complex to recover the raw materials [88]. Of course, this applies in the same way to the electronic components in pneumatic valve terminals or sensors.

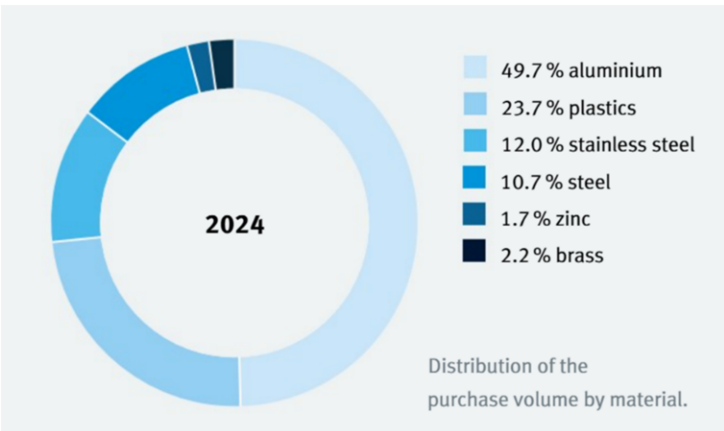


Figure 10. Distribution of production materials of Festo by weight [9]

To illustrate it with another example. Only a few magnets are used in pneumatic drive technology. Although magnet-free electric motors are now available [89], rare-earth magnets [90] are commonly used for powerful motors. And rare-earth elements are critical raw materials [81, 83].

5. SUMMARY AND OUTLOOK

Significant changes are required for pneumatic drive technology to successfully complete the energetic transformation towards CO_2 neutrality on a broad scale. This applies in particular to the high energy and thus CO_2 consumption during the use phase. Controlled pneumatics with solutions such as ECO drive with the VTEM Motion Terminal or Smart Switching Lite as an option for the new VTUX valve terminal offer potential for this. This is associated with an increasing integration of sensor technology, ideally without any significant impact on reliability and robustness of pneumatic systems. This is important in view of a second megatrend in addition to environmental sustainability, which is currently transforming fluid power technology: digitalization. There are definitely opportunities for pneumatics here – even and especially in competition with electric drives.
However, this requires pneumatic research and development to focus more on the integration of sensor technology and the additional customer benefits that can be derived from it (Soft sensors, Functional Mock-Up Units (FMU), predictive maintenance, health index, RUL, ...).

On the other hand, pneumatics offers a number of fundamental advantages that may be relevant in terms of ecodesign. Pneumatic products, for example, are robust and reliable – as significantly fewer components are required for a pneumatic movement compared to an electric movement. System reliability is calculated by multiplying the reliability of all individual installed elements. Another example of the advantages of pneumatics is the simple and cost-effective commissioning. With a 24V power supply (if there is a power supply at all), pneumatic components are suitable for the extra-low voltage range [91]. They are therefore of course subject to the requirements for general product safety [92] - but not the Low Voltage Directive [93]. Accordingly, no qualified electrician in accordance with DGUV V3 [94] is usually required.

Figure 11 concludes this paper with a general comparison of electric and pneumatic drive technology (based on [95 and 96]) as well as a specific comparison in terms of environmental sustainability. In times of change to climate-neutral and resource-efficient production combined with the digital revolution, it is important to reduce the weaknesses of pneumatics – without reducing its strengths.

Criterion	Standard Pneumatics	Smart Switching Lite	Electric Spindel Drive	Electric Tooth Belt Drive
System Properties				
Number of Positions	2-3	2	any desired	any desired
Quality of movement	★★	★★	★★★★★	★★★★
Dynamics	★★★★	★★★★	★★★	★★★★★
Force	★★★★	★★★★	★★★★★	★★
Accuracy	★★★	★★★	★★★★★	★★★
Flexibility	★	★★	★★★★★	★★★★★
Power density	★★★★★	★★★★★	★★★	★★★
Simplicity, Installation effort	★★★★★	★★★★	★★★	★★★
EMC/Ex-proof	★★★★★	★★★★★	★★	★★
Acquisition costs	★★★★★	★★★★★	★★	★★★
Operation costs	★★	★★★	★★★★★	★★★★★
Reliability and Robustness				
Reliability	★★★★★	★★★★	★★★	★★
Load stiffness	★★	★	★★★★★	★★★★
Overload capacity	★★★★★	★★★★★	★★	★★
Robustness against changes of environmental conditions	★★★★★	★★★★	★★★	★★★
Avoidance of decentral heat generation	★★★★★	★★★★★	★★	★★
Noise level, Low vibration	★★	★★	★★★★★	★★★★★
Environmental Sustainability				
Energy Efficiency	★★	★★★	★★★★★	★★★★★
Load-dependent energy consumption	★★	★★★★	★★★★★	★★★★★
PCF c2g	★★★★★	★★★★★	★★	★★★
Circular Economy (CE)				
CE - RePair	★★★★★	★★★★★	★★	★★★
CE - ReUse	★★★★	★★★★	★★★	★★★
CE - ReMan, FeFurb	★★	★★	★★★★	★★★★
CE - ReCycle	★★★★★	★★★★★	★★★	★★★

Figure 11. Comparison of pneumatic and electric drive technology

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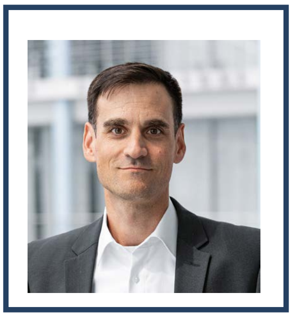
Biographies





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