EnEffAH

Energy efficiency in production in the drive and handling technology field

Basic principles and measures

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Preface

Climate protection, energy efficiency and using resources responsibly have long been express political goals in the Federal Republic of Germany. As early as 1995, Germany undertook to reduce greenhouse gas emissions by 25 percent by 2005 (relative to the figures from 1990) at the climate summit in Berlin.

In addition to sustainable use of resources to protect our environment and the global climate, reaching the climate protection goals was also intended as a way to reduce mankind's dependence on finite energy sources. As a country with low natural oil and gas fossil fuel resources, Germany is particularly keen to reduce this dependence. The most promising method for the long term is economical and efficient use of energy and utilising renewable energy sources. As the energy supply is vital for industrial production, it must develop energy-efficient production technologies and products if it is to remain viable in future.

Industry accounted for roughly 43 percent of the total electricity consumption in Germany in 2010. Electricity consumption and energy requirements play a major role in automation technology in particular. The **EnEffAH (Energy Efficiency in Production in the Drive and Handling Technology Field)** project contributes to rational use of energy and saving energy in end user sectors. Using the solutions for energy-optimised system operation developed in the project will significantly increase the energy productivity in the industrial sector.

The **EnEffAH** research and development project was funded by the German Federal Ministry of Economics and Technology (BMWi) as part of the 5th and 6th German Government Energy Research Programme. It was organised by the Energy Economy and Energy Efficiency department of the project organisation Jülich, with the funding priority "Energy efficiency in industry".

Technology and methods play an important part in optimising energy use. The right choice of technology (effectiveness), and correct operation (efficiency) determine how much primary or end-use energy is required to provide the energy services required in production processes (heat, power, light and information).

Efficient use of energy in automation by using intelligent mechatronic systems and components, employing low-power technologies and optimal system design is essential and a challenge for maintaining and strengthening competitiveness of the German industry, which is based on automation. It is also an important contribution to reducing the consumption of natural resources and the associated strain on the environment, in particular by emissions of greenhouse trace gases.

The institutes and industrial companies wish to express their gratitude to BMWi and the project organisation Jülich, whose funds and support made this project possible (funding code: 0327484A-E).

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Contents

1.1 The joint project

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EnEffAH stands for "**Energy Efficiency in Production in the Drive and Handling Technology Field**" and is a joint project as part of the German Government's energy research programme.

Various companies and institutes cooperated as part of the EnEffAH project in order to develop fundamental energy saving concepts and system optimisation processes, which can be used in pneumatic and electric drive and handling systems.

Project goal

The goal of the project is to develop methods, tools and products to guarantee energy-efficient automation. The correct selection of technology (effectiveness), and the correct operation (efficiency) are critical for energy efficiency and functionality. Based on an overall study, the project investigated both pneumatic and electric drive technology, including the functional chain and the use of these technologies in the field of handling and robotics.

Pneumatic drive technology uses compressed air as a drive medium, and is characterised by its environmentally friendly and simple design. When generating compressed air, it is important to use efficient compressor stations with optimised compressed air preparation and appropriately designed compressed air systems for forwarding and distributing the compressed air. Synergies with other energy systems should also be noted, e.g. use of waste heat by heat recovery systems.

Especially for applications which require large holding forces for extended periods, pneumatics has a major advantage compared with electric drives, as they require constant electricity consumption to generate power and become very hot.

Previous optimisation activities in the compressed air sector have primarily involved generation and distribution. Use of compressed air itself was not the focus of the considerations. This project is to include all elements of the pneumatic functional chain. The application is an important component of optimisation measures, based on the following tenet:

If you don't consume it, you don't have to generate and distribute it.

For **electric drives**, efficiency-optimisation measures to date have largely focused on applications with a high level of machine usage, e.g. pumps with constant loads in continuous operation, but not in start-stop operation, as is the case in positioning or pick-and-place applications. Energy recovery or intermediate storage creates significant potential energy savings in this area.

All energy optimisation measures developed as part of the EnEffAH-Projekts are based on the **overall assessment of the system** – i.e. for pneumatics, from compressed air generation, to preparation and distribution and finally application. To ensure that the findings can be transferred into practice, methods and simulation tools were developed to support planning and implementation.

By using the latest technologies and methods, which also permit the integration of system elements in intelligent mechatronic power units, **highly innovative, flexible products for energy-efficient operation** in automation technology can be produced.

1.2 Project partners

Festo AG & Co. KG
Festo is a leading supplier of pneumatic and electric automation technology. As a family owned business with headquarters in Esslingen, Germany, Festo has become the global market leader in its sector over the past 50 years thanks to innovation and problem solving expertise in the field of pneumatics and electric drive technology, as well as a unique range of industrial training and vocational education programmes. The product range comprises ready-to-install subsystems as well as customised solutions for the automotive, electronics, food, packaging, biotech, pharma and process industries.
www.festo.com

Kaeser Kompressoren AG
Founded in 1919, today Kaeser is one of the world's leading manufacturers of compressors and compressed air system providers with about 4000 employees. The product range includes stationary screw compressors, construction compressors, piston compressors, compressed air management systems, dental compressors, vacuum pumps, rotary piston blowers, filters, dryers, pneumatic tools and accessories. In addition, the company also provides services such as consulting, planning and compressed air requirement analyses.
They aim to supply compressed air with maximum energy efficiency.
The company directors are Dipl.-Wirtsch.-Ing. Thomas Kaeser and Dipl. Wirtsch.-Ing. Tina-Maria Vlantoussi-Kaeser.
www.kaeser.com

Metronix Meßgeräte und Elektronik GmbH
Metronix specialises in developing and manufacturing digital drive controllers for servo motors. Since its establishment in 1976, Metronix has developed and produced intelligent industrial electronics for drive technology and measurement and control technology. Metronix brings a high-performance range of digital drive controllers to the market. Metronix is a wholly owned subsidiary of the US company Cooper Industries and is part of the Cooper Tools division. Cooper Tools has multiple production sites in Germany, Europe and the USA. Metronix develops and produces products in its Braunschweig plant, which employs a staff of 65.
www.metronix.de

Institute for System Dynamics – University of Stuttgart
The institute's research focuses on the analysis of system dynamics and ways to influence them. System theory, modelling, simulation, control technology and optimisation methods are applied and further developed. They research a wide range of areas such as mechatronics, process technology, communication and biology. The institute's philosophy is to implement the theoretical findings in practical applications. Success is based on funding and support by many public and industrial partners.
www.isys.uni-stuttgart.de

Fraunhofer Institute for System and Innovation Research ISI
Fraunhofer ISI researches the short and long-term developments of innovation processes and the social effects of new technologies and services. The work is based on a broad academic expertise as well as interdisciplinary and systematic research approach. Topics also include investigations of the use of energy-efficient technologies and analysis and evaluation of innovative approaches in industrial production.
www.isi.fraunhofer.de

Institute for Power Electronics and Electric Drives – University of Stuttgart
The ILEA works on topical areas of power electronics, control engineering and electric drives. Besides energy efficiency, research fields include the control of electric drives, in particular vehicle drives and high-speed three-phase drives, methods for encoder-free position detection, processes for highly dynamic measurement of high currents, circuit topologies and control processes for converters and process current sources and the reliability of power electronics systems.
www.ilea.uni-stuttgart.de

From left to right

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Matthias Doll, Gerhart Hobusch, Michael Ohmer

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1.3 BMWi and Project Management

The **German Federal Ministry of Economics and Technology (BMWi)** defines “Innovation and new energy technologies” of the 5th energy research programme and “Research for an environmentally friendly, reliable and affordable energy supply” of the 6th and current energy research programme as the research funding priorities for the years to come.

The funding programme is designed as a reaction to the energy industry and energy technology challenges of the future in Germany by providing energy on a sustainable basis. In order to secure the energy supply in the medium and long term, renewable energy sources are to be boosted, the energy requirement is to be reduced and energy efficiency is to be increased. The development of climate-friendly and efficient technologies plays a key role here.

The Project Management Jülich supervises much of the research funding in the area of energy, including the EnEffAH project, on behalf of several government ministries. In addition to this, there are other funding programs for renewable energy sources, rational energy use and power plant technologies.

Finally, the project organisation Jülich is also involved in European and international research management. For example, it is involved in four ERA-NET projects of the European Commission, and coordinates three projects. At an international level, Project Management Jülich represents its clients in numerous committees, including in the International Energy Agency (IEA) and the International Partnership for the Hydrogen Economy (IPHE).

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1.4 Aims of this paper

The increase in energy efficiency of drive and handling technology is a complex area and includes a broad range of technical and organisational topics. In many companies, there is an urgent need for action due to rising energy prices and an increased environmental awareness. Energy consumption and costs can be reduced significantly with simple means.
However, existing potential often goes unused.

This paper helps industrial users to evaluate the energy efficiency in their own applications, and to better understand and identify the options for improving energy efficiency. **Besides increasing awareness for the subject, it is also intended to provide information on options to design energy-efficient drive and handling technology.** In addition to the familiar questions, this paper also contains research results from the EnEffAH project and provides information for a better understanding of energy efficiency in drive and handling technology.

In this paper, the discussions on the topic of energy efficiency spans across several technologies, including both pneumatic and electric drive and handling technology.
At the same time, the paper aims to not only cover sub-areas such as energy provision and energy use, but the **complete functional chain** including preparation and distribution, taking the entire system into consideration.

As part of the project, it became clear time and time again that questions on increasing energy efficiency must be viewed in an overall context, and parameters must often be incorporated in detail to provide final statements on potential efficiency, savings and economy. That is why this paper should only be considered as a **guideline**, as options and savings potential must always be discussed based on the respective circumstances in individual cases.

2.1 The significance of energy efficiency for companies

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The energy-efficient design of production systems is becoming ever more important, not only because of climate change, increasing scarcity of fossil energy resources or political goals. Improving energy efficiency often means enhancing a company's own competitiveness. Changing customer requirements for energy-efficient machine and plant technology can be taken into account, company internal energy saving goals can be met, and dealing with the topic of energy efficiency often promises significant cost savings. It can have additional advantages, e.g. processes are more transparent and improvements in areas other than energy productivity can be achieved. From an entrepreneurial point of view, the following are particularly promising:

- Decreasing energy consumption and power costs,
- Improving the transparency of the energy flows in the company,
- Reducing the dependence on the energy supply and energy price fluctuations,
- Fulfilling customer requirements and improving customer loyalty and
- Improving the image of the company.

Efficiency measures are varied and can range from replacing a single component to redesigning an entire drive system, to completely revising a process. Simple organisational measures such as switching off systems or parts of systems or regular maintenance intervals can result in significant improvements. Energy efficiency should be incorporated in the planning process of a plant at an early stage to optimise the results.

Experience has shown that energy efficiency measures often create significant economic potential that is often not exploited and needs to be unlocked. There are numerous reasons for this, including aspects such as:

- A **lack of awareness of the cause and the total energy consumption and power costs** and possible measures for saving.
- A **focus on partial systems** instead of considering the system as a whole. As a result, parts of the system are often optimised separately from one another, without taking the overall efficiency of the system into account.
- A **trade-off between various systems and components** is often made solely based on investment costs. A favourable purchase price frequently comes at the cost of efficiency. In the long term, inefficient components lead to high power costs, which can result in far higher overall costs over the lifetime of a system.
- Setting a relatively **short pay-back time** (up to 3 years), without considering the actual overall period of usage. For an appropriate evaluation, the internal return rate must also be taken into consideration to obtain an adequate idea of the economy.
- **Insufficient incentives:**
  The problem, particularly in the area of central compressed air supply, is that wholesale attribution of power costs to individual cost accounts creates incorrect incentives. For example, Purchasing or Facility Management aims to purchase compressor stations at the lowest price possible, while Production must bear the relatively high power costs that are allocated to its budget.

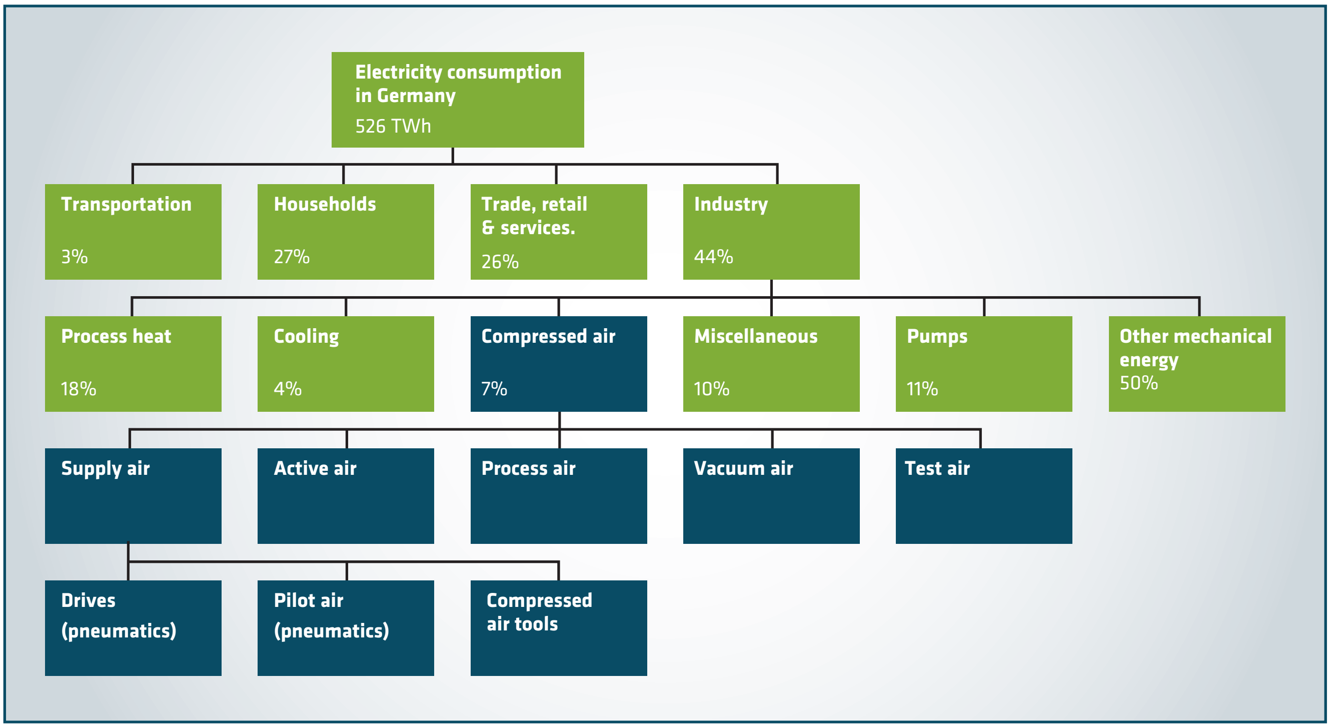
Raising awareness plays an important role in overcoming these obstacles. Typical counter measures can be introduced by educating and training employees, visualising energy consumption of individual components or implementing company-internal incentive systems. The concept of energy efficiency must be shared by all departments in the company (Production, Maintenance, Purchasing, etc.). Corporate management has a key part in this, as it must create the conditions which enable their staff to address the subject and allow energy efficiency to become a permanent part of the corporate culture.

2.2 Differentiation of drive and handling technology

A look at the industrial electricity consumption in Germany underlines the role of drive and handling technology in increasing energy efficiency.
In 2008, the industrial sector accounted for a total current consumption of approximately 233 billion kilowatt hours or 44% of the German electricity demand.

The role of drive technology is very significant in this respect as over two-thirds of the industrial electricity demand is incurred to provide mechanical energy, including roughly 17 billion kilowatt hours for generating compressed air alone. The term "drive technology" includes a wide range of applications, from motors with a power consumption of several 100 kilowatts to micro-applications with low wattages or very low compressed air consumption.

Pneumatic drive technology as part of compressed air systems
Compressed air can be used for a large number of different applications. It can be used as supply air for driving tools and pneumatic machines, as active air for transporting materials, as a process medium, to generate a vacuum or for test applications.
The importance of these purposes varies greatly depending on the industry and company. In the past they have been treated together, which resulted in a distortion when comparing technologies (pneumatic or electric drive and handling technology). Most of the compressed air used in industrial applications is used for pneumatic tools as active air or process air. While there are no verified statistics on the energy consumption of pneumatic applications within the compressed air technology sector, an average **of roughly 20% of the entire compressed air consumption is assumed** as realistic.This average can vary significantly depending on the company, system and application.



Classification of compressed air according to its purpose	
Compressed air type	**Description**
Supply air	Supply air describes air used to drive tools and pneumatic machinery. The energy from the compressed air is transferred to mechanical energy. Fundamentally, all applications come under this category. Pilot air (e.g. controlling valves, slides, flaps etc.) is also attributed to supply air.
Active air	Active air refers to air which is used to transport substances, media etc.. Active air can be further broken down into conveyor air, which actually transports materials, and active air in a broader sense, whewhere the air is used to blow substances out of a tool or a machine (e.g. for surface treatment).
Process air	Process air refers to air which is used for integration in processes. This also includes use of the air itself, e.g. for drying, cooling or ventilation.
Vacuum air	Vacuum air is air which is used to create underpressure via compressed air.
Test air	Test air is used for testing and checking purposes.

It is assumed that an economic savings potential of 50% of the overall energy consumption can be achieved across all compressed air applications. The energy consumption question is closely related to the economic aspect, as roughly 70% of the lifecycle costs of a compressed air station are incurred for energy consumption. In Germany, leakages alone cause up to 30% of compressed air consumption, which can quickly add up to power costs of tens of thousands of euros per annum.

The areas of application of electric motors are just as varied, as they can be used as power supply units for compressors, centrifuges, pumps, fans as well as for linear axes in automation technology. Major savings are also possible for typical electric motors. In addition to using high-efficiency motors, variable frequency electric drives, for example, is viewed as a significant potential for improvement (up to 50%).

The EnEffAH project and this paper focus on drives which are used for industrial automation in inching operation, such as linear axes or semi-rotary drives, and their respective functional chains, including compressed air supply, distribution and preparation. Applications include motion and holding as typical handling functions per VDI 2860. In accordance with this definition they are distinct from applications with, for example, manual tools or stationary electric motors.

3.1 Overview of the entire system

3

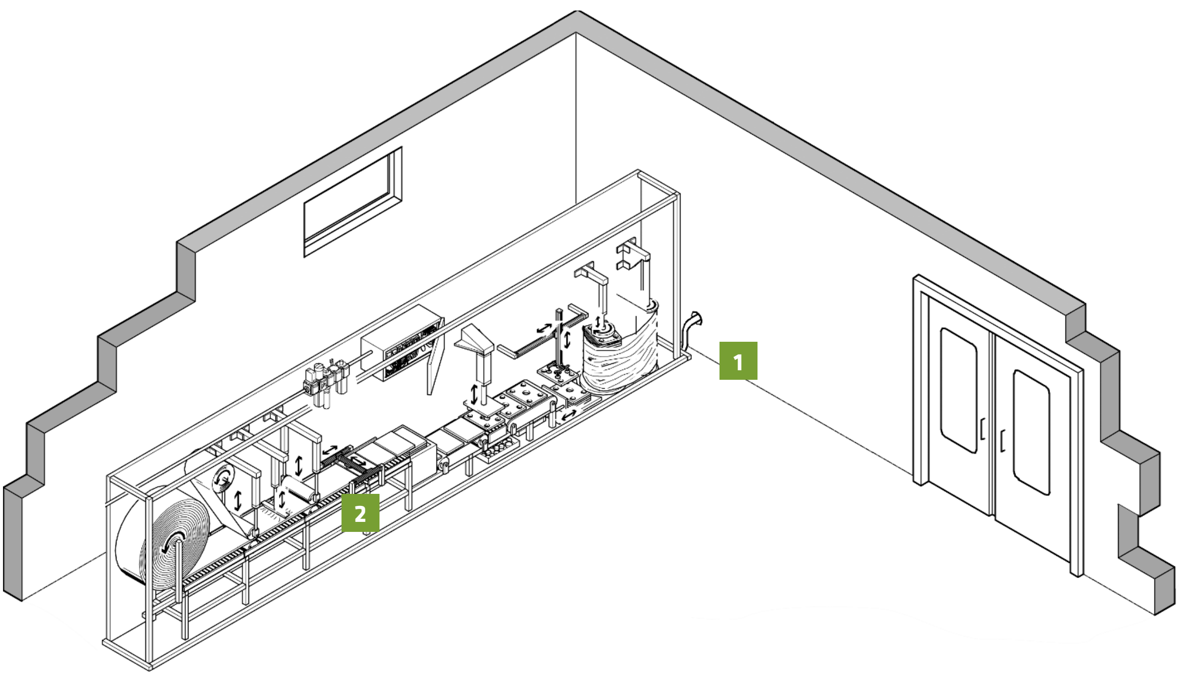
A variety of applications in drive and handling technology can be implemented via various technologies, be it pneumatic, electric or hydraulic. **The EnEffAH project focuses on pneumatic and electric drive technology,** i.e. the use of compressed air and electric current as energy media. Every technology has a specific structure, requires a different infrastructure or control concepts and the advantages differ from one application to another. Direct comparisons of these two technologies therefore always depend on the respective specific requirements and cannot be generalised.
The section below introduces the two systems with their individual elements.
This is followed by the particular advantages of each system.

3.1.1 Entire electrical system

The structure of the overall system of electric drives differs significantly from the structure of pneumatics. Compared with pneumatic systems, energy provision and distribution are far simpler, while the structure of the actual drive system is often more complex. As a result, electric drive systems are often more expensive to purchase than the pneumatic equivalent with similar functions.

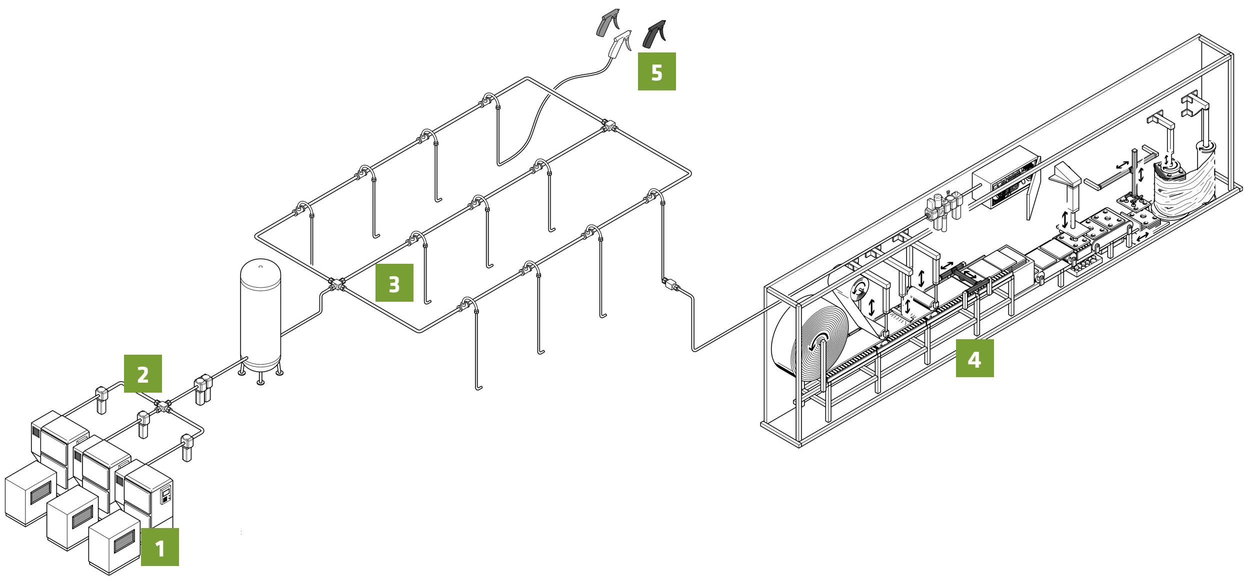
1 Energy provision and distribution
Most electric energy is provided by an external energy supplier; local self-supply is rare. Energy is distributed within a building via electric cables, which results in minor losses. In addition to the mains voltage, some electric systems require a low DC voltage, which is provided via decentralised power supply units.
The average energy purchase price for a company in Germany is currently roughly 10 cents/kWh.

2 Application
Applications can be varied, however, most systems consist of three main components: A servo controller or a control unit regulates or controls the system. An electric actuator, generally a rotating or linear electric motor, converts the electrically supplied power into mechanical drive power. The mechanical system (a guide, bearing or a gear unit) converts this into the required movement as the third component.



3.1.2 Entire pneumatic system

Compared with electric systems, pneumatic systems require a more complicated infrastructure in terms of generation, preparation and distribution. Compressors, refrigeration systems, dryers, filters, buffers and other components are required to operate a compressed air system.
By contrast, the actual drive is simple and sturdy (with regard to extreme operating conditions).
It has a high power/force density and is therefore more compact.



1 Compressed air production
The compressor takes air from the ambient atmosphere to a higher pressure level than the surrounding air. Due to thermodynamics, this produces a great deal of heat which can be made use of via a suitable heat exchanger, e.g. for heating or as process heat. The integrated recooler then cools the compressed air to almost the ambient temperature.

2 Compressed air preparation
The compressed air generated is dried and filtered. Residual oil and dust particles are removed in accordance with the compressed air quality class required.

3 Compressed air distribution
In a main network, the compressed air is distributed throughout the entire plant. A reservoir serves as buffer volume to compensate for short-term fluctuations in compressed air consumption.
Various network topologies (e.g. ring lines, star lines) make distribution as efficient as possible.

4 Application
In the application, compressed air – besides other functions – is used to drive pneumatic cylinders, which perform tasks in drive and handling technology.

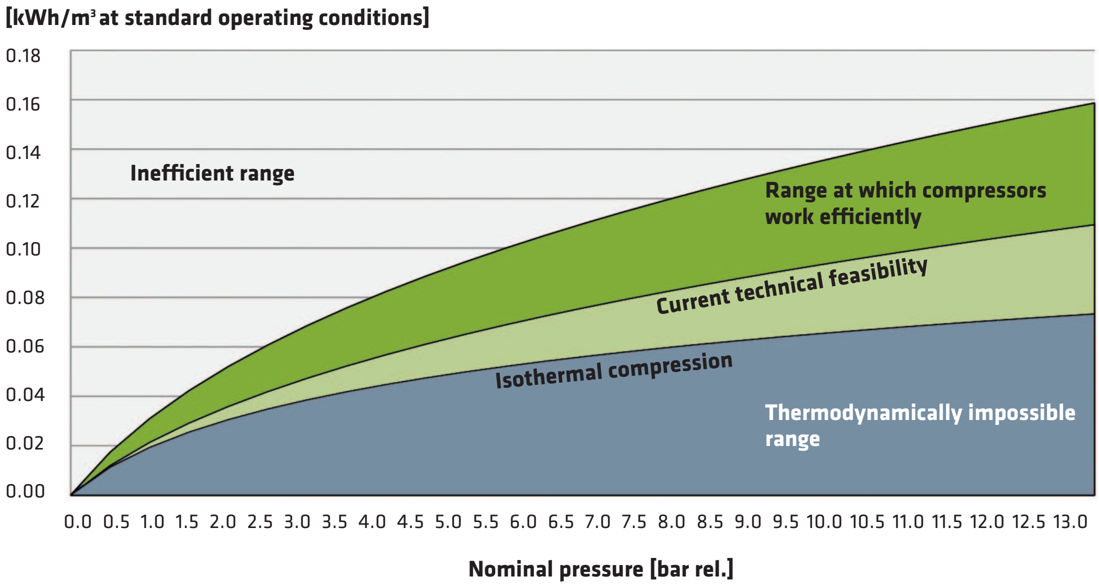
5 Active air/sealing air and compressed air tools
Compressed air tools such as compressed air screw drivers consume large amounts of compressed air, and should only be used where required.
Active or process air is another major consumer. The compressed air is not used actuation or handling, but it fulfils other functions (e.g. sealing air, excess pressure in a machine, inflating bags, cooling components).

Costs for compressed air
Investigations by the European Commission from 2009 reveal a price range from 0.6 - 10 cents per standard cubic metre in Europe (1000 litres at 0 bar relative (=1 bar absolute) compressed to 7 bar relative). The high fluctuations depend on many factors, the most important of which include:

- Energy efficiency of the system – well-designed large compressor stations only need 0.1 to 0.12 kWh/m at standard temperature and pressure at 7 bar relative (excess pressure).
- Type of compressor used and the compressor control unit
- Size of the company or the size of the compressors
- Power costs

Experience shows that at a current compression to 8 bar absolute for a value of 1.5 to 2 cents per cubic metre at standard operating conditions is a good average basis for sample calculations for efficiently designed larger systems. Converter, current and thermal losses in the compressor and the purchasing (~13%) and maintenance costs (~12%) for the compressors and the compressed air preparation are already included in this value.
It can therefore be used generally and offers a basis for comparing the costs of pneumatic and electric energy.

Specific power consumption for air compression



Pressure indication – absolute or relative?
Specifications of pressure levels in compressed air technology often do not explicitly mention whether this is absolute pressure (relative to the vacuum) or relative pressure (relative to the ambient pressure). In general, relative pressure information is used. Including the relative level in the specification used creates clarity.

Compressed air units
Compressed air is specified in litres (l) or cubic metres (m^3). The most common approach, which is therefore also used in this paper, is to specify the amount of compressed air in standard cubic metres (m^3 at standard operating conditions).
This is one cubic metre at standard conditions (0°C, 1.01325 bar, 0% humidity per DIN 1343), which is then compressed to operating pressure by the compressor (generally 7 bar relative – i.e. excess pressure). The air volume (operating volume) is reduced accordingly during compression.

An air flow rate (e.g. air consumption) can be specified if the amount of compressed air is described in units of time. The unit is generally standard cubic metres (or standard litres) per minute (m^3/min or l/min at standard operating conditions).

In addition to the standard volume per DIN 1343, there are other standards to describe the air condition but which have different points of reference. This often leads to confusion and can cause incorrect design. For example, in addition to DIN 1343, there is also standard volume per DIN/ISO 2533 as well as ISO 6358 (both have slightly different points of reference or temperature and pressure). The delivery rate of compressors, relative to the intake rate, is also specified in standard volumes in accordance with ISO 1217. The standard defines this as 1 bar, 20°C, 0% air humidity.

DIN 1343 defines the conversion of the various volume specifications.

Optimisation approach

Exergy flow diagram

Besides the development and implementation of energy efficiency-increasing measures, the presentation of the energy quality of systems is gaining ground. The efficiency specifications of certain systems can only be compared, evaluated or classified if a consistent and uniform description of the energy interactions within a process is available.

In the compressed air technology field, energy flow diagrams are frequently used for this. Starting from an energy source, they show the energy flows along various stations within a system, which each represent a sub-section of the system (e.g. compressor, after cooler, dryer, network). The width of the arrows is proportional to the flow, which guarantees good legibility. In spite of its clarity, this approach has weaknesses. In pneumatics, the thermodynamic variable “energy” does not permit any statement to be made on the usable work a pneumatic system can perform. This is in particular due to the fact that the energy content in a given pneumatic condition is a function of the air temperature, but not of the pressure. However, it is especially the pressure that forms the driving parameter for performing work in pneumatic systems. While high temperatures lead to a high energy content in the system, the energy cannot be used pneumatically.

This shows that it is impossible to make a reliable statement on the pneumatic effectiveness of a status based on energy studies.

One method with which the above mentioned insufficiencies can be overcome is to use a different thermodynamic factor, i.e. **exergy**.

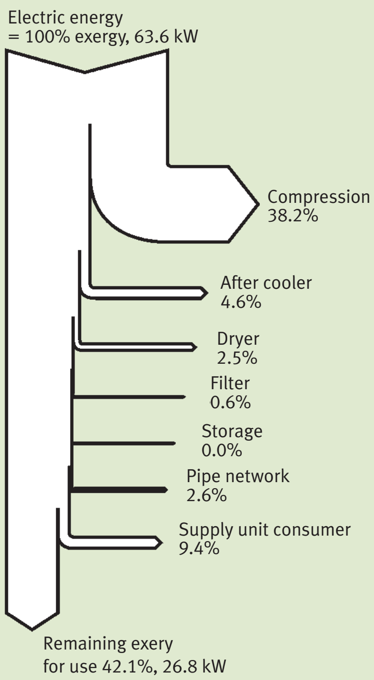
It refers to that part of a system which can perform work if the system is brought into balance with the environment. Thus, exergy forms the usable proportion of the total energy, the non-usable proportion is called anergy. Exergy is a status variable, but not a conserved variable, i.e. exergy can be converted to anergy and thus be lost.

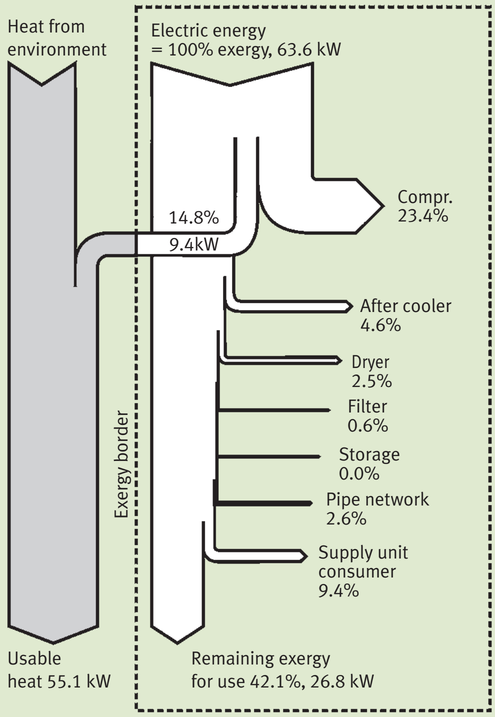
As the effectiveness of energy always requires an energy gradient compared with the environment, and this needs to be taken into consideration when calculating exergy, the following information is required to calculate the actual exergy status: the ambient pressure p_{atm} and ambient temperature T_{atm}, as well as a total of four variables which describe the current status a:
the supplied electric energy P_a (= pure exergy), the absolute pressure p_a, the temperature T_a and the corresponding volume flow Q_a. These specifications are used to calculate the exergy as

$$E_a = P_a + Q_a \rho_a c_p \cdot (T_a - T_{atm}) + Q_a \rho_a T_{atm} \cdot \left(R ln\left(\frac{p_a}{p_{atm}}\right) - c_p ln\left(\frac{T_a}{T_{atm}}\right)\right)$$

With exergy important events in the functional chain can be determined: consumption of electric energy by a process, pressure changes, temperature changes and changes in the flow, e.g. due to a leakage. By comparing two statutes the exergy loss between them can be calculated. When this is expressed as a percentage of the initial exergy, it gives the percentage loss at every station in the functional chain.

The figure on the left shows an example of an exergy flow diagram for a pneumatic system. Most of the exergy is lost on compression – 38.2% in the example shown here. At the end of the functional chain, an effective remaining exergy of 42.1% from the initial exergy is available for the application.





When the air is compressed, a lot of the heat development occurs in the compressed air chain due to thermodynamic effects. An essential factor for the efficiency increase of compressed air systems is therefore the integration of a heat recovery system. The heat can then be used for indoor heating or e.g. as process heat.

Exergy and heat can be represented in one diagram if the usable exergy proportion from heat recovery is routed to the left. It is used to exploit a heat flow from the compressed air. Physically, this process is the same as a heat pump (top figure). The example shown here results in a usable amount of heat of 55.1 kW at the end of the functional chain, in addition to the usable exergy.

The exergy flow diagrams as shown in the figure can help to make the efficiency of pneumatics or compressed air applications clearer and easier to compare, also with other technologies.

3.2 Selection of suitable technology

Selecting the technology used for an application is a key decision. In principle, most applications in drive and handling technology can be implemented both pneumatically and electrically. Increasing standardisation of individual components makes technologies interchangeable. Selecting a suitable technology for a specific application plays an important role for the efficiency of the entire system. Both technologies have specific advantages and disadvantages, which is why no general statement can be made on the benefits of a technology. In addition to the actual function, factors such as the force required, acceleration, cycle time, precision, holding duration, and many other factors are necessary to select the more efficient technology or drive solution.

	Pneumatic	Electric
Advantages	· Sturdiness and simple design · Load bearing capacity and resistance to overload · Low performance/weight ratio and high power density · Continuous peak force · Force-free holding · Central heat production, most of which is usable	· Efficient conversion of electric to kinetic energy · Braking energy can be used (energy recovery and storage) · High dynamic response due to rapid force build-up · High positioning accuracy · Good adjustability · High flexibility due to specification of the precise movement · High load rigidity · Control insensitive to influences of noise
Disadvantages	· Noisier (exhaust air fitting) · Condensate (drying) · Air consumption costs of the overall system with active air and process air and pneumatic tools.	· Decentralised heating of components, almost no use possible, partial cooling of control cabinets required

Based on these advantages and disadvantages, and taking the operating methods (closed-loop/open-loop) into account, it is clear that it is difficult to compare the two technologies directly with one another. That is why the two technologies are also referred to as complementary technologies. Bearing in mind the abovementioned points, a technology cannot be selected based on energy aspects alone; other properties of the technologies play an important part and must be incorporated in the decision:

Technical requirements	Stroke range, speed, force, overload resistance, load bearing capacity, performance/weight ratio, precision, control characteristics/dynamic characteristics, load stiffness
Environment	Dust, moisture, electromagnetic compatibility, sturdiness/sensitivity, explosion protection
Installation costs	Price, commissioning, installation, power supply, power supply unit/transformer, compressor, compressed air network, air conditioning, service life
Operating costs	Power costs, maintenance, operation

Comparison of the technologies based on energy aspects

No general statement can be made on energy consumption. Energy consumption always depends on the components which were selected during the design process. Although the drive characteristics of both technologies are significantly different, there are many attempts to compare the two technologies. These comparisons can be very different, depending on the parameters selected for the comparison. There are two main reasons why the comparisons are often incorrect:

- Comparison under impractical conditions
- Non-comparable design of the drive components, which plays a crucial role for the comparison.

For example, an efficiency of 80% – 90% is attributed to electric motors, while an efficiency of approx. 6% – 10% is often assumed for compressed air. Based on these specifications, an incorrect conclusion is drawn, i.e. that pneumatic applications require 8 to 15 times more energy than the corresponding electric solution. However, this ignores the fact that the assumptions made for electric drives only apply to motors in stationary operation (e.g. pumps, fans, etc.). For inching operation, which is common in handling technology, the efficiency of electric components is far lower. Based on this data, electric drive technology cannot be compared with pneumatics. Also, calculations which indicate that the efficiency of pneumatic applications is between 6–10% are often highly questionable (*see "Exergy flow diagram" – page 20)*.

Further challenges for a comparative consideration of the two technologies include both the operating method and the parameters selected.

Method of operation

While electric drives are always operated in closed-loop operation, pneumatic drives are generally operated in open-loop operation. Both technologies are subject to several influences that affect the energy consumption.

Parameters

If there are precise requirements for the travel path (i.e. the motion characteristics) of the drive, such as a maximum speed or maximum acceleration, they are easy to implement with a closed-loop electric drive. With open-loop pneumatic drives this can only be implemented partially via the design, which can lead to a disproportionately high air consumption. In these cases the requirements should be checked to establish if they are really relevant or not.

However, the main difference between electric and pneumatic drives is that the latter offer very high end position forces in standard operation. This end position force is not available with electric drives due to the closed-loop operation, which means that the motion characteristics are not comparable. Comparability is only possible if both drives have the same end position force (e.g. no end position force or full end position force).

Division of a positioning process into the handling functions “moving” and “holding”

A positioning process primarily consists of the “moving” handling function. If an additional force must be applied in the end position, the “holding” handling position is also required. When comparing the energy consumption for a positioning process, both functions must therefore be considered.

“Moving” function

This task consists of moving a load a certain distance within a specific time. The parameters (required movement time, speed, acceleration, etc.) affect the energy consumption of electric and pneumatic drive systems differently. As a result, no general statements can be made on energy efficiency.

For movement, an electric drive system requires a specific amount of energy. This depends on multiple factors, such as the load to be moved and the losses of the components, as well as the parameters of the movement itself, e.g. the movement duration. The closed-loop operating mode allows the movement as well as the energy consumption to be influenced directly.

In contrast to this, a pneumatic drive system requires a certain amount of compressed air for the movement, which can be converted to energy. The load to be moved and the friction of the components are not of major importance. The movement cannot be influenced precisely, as it depends on the design and the settings of flow control valves. In open-loop operation, the cylinder is always completely pressurised, which, when compared with electric drive systems, can lead to a distorted result, as most of the compressed air used for the cylinder is used for the end position pressure (holding function). If we only consider and compare movement, the cylinder could be controlled such that it is force-free at the end of the stroke. Under these circumstances, the air consumption of a pneumatic cylinder can be reduced by up to 85%. This can be achieved practically, by pressurising and exhausting the cylinder chambers while the piston is moving. That requires suitable switching strategies, but it also permits a more effective use of the energy available in the compressed air, in particular the expansion energy (see Chap. 4.4.4 and Section 4.4.4.3). However, these switching strategies have not yet been implemented in practice.

Holding function
This task consists of applying a required force in an extended status for a specific period, e.g. holding a load or compensating for an interfering force. With pneumatics there is always a maximum force in the end position due to the open-loop operation, while electric drives are generally force-free in the end position (unless interfering forces apply). As such, a pneumatic system, as well as providing a movement, also provides a maximum force in the end position. This force is always present, whether it is needed or not (e.g. to hold a load). Electric drives, on the other hand, only supply this force when it is required, as they run in closed-loop operation.

For the holding function, a few equations are sufficient to calculate the energy demand of the electric motor and the energy requirement of the pneumatic drive. The following section explains the interrelation of the energy consumption and the application parameters (force, holding duration, stroke length).

The energy consumption of an **electric drive** is largely a quadratic function of the required force and increases linearly with the holding duration. The stroke length of the drive does not play a role.

By contrast, in **pneumatic drives,** the energy consumption does not depend on the holding duration as this is a force-free. It is only a linear function of the required force. However, it does depend on the stroke length as that affects the pressurised volume. The energy consumption of the pneumatic drive is calculated as being the energy consumption at the compressor using the compressed air index and the air consumption.

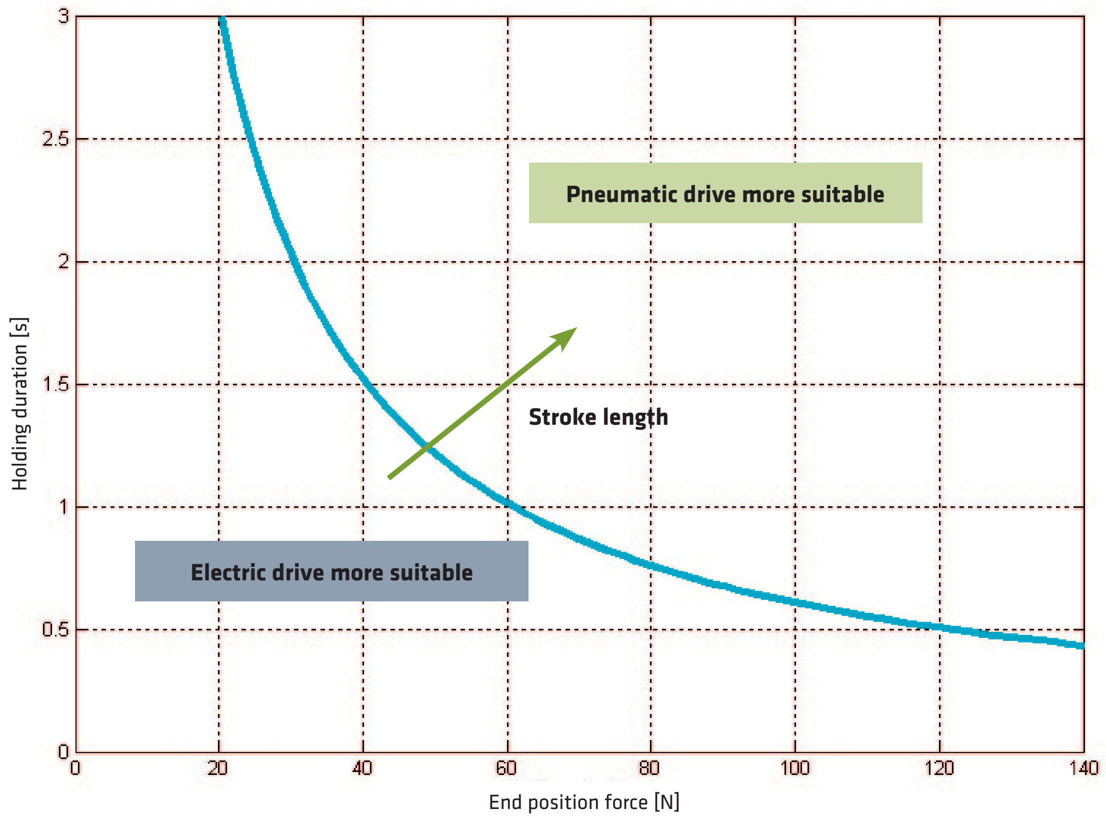
To select the technology with the more efficient energy consumption, a decision limit can be determined. To do so, tthe energy consumption of the two technologies is **compared.**

The decision limit depends on the required end position force, the stroke length and the holding duration, and represents a level equation in three-dimensional space. For a specific stroke, the equation is simplified to a two-dimensional problem, which is illustrated in the following figure. The blue line shows the decision limit; below it, electric drives are more efficient and above it pneumatic drives are more efficient. As the stroke length increases, this curve shifts upwards.

Accordingly, the following **rules of thumb** can be formulated:

The shorter the stroke length,
the greater the end position force and
the longer the holding duration,
the more efficient pneumatic
drive technology is.

The greater the stroke length,
the lower the end position force and the shorter
the holding duration,
the more efficient electric
drive technology is.



Application-specific efficiency ranges for the holding handling function in both technologies.

The two different handling functions show that no generally valid statements can be made on the benefits of one technology. Instead, individual checks are required for every application to determine which technology is more efficient taking all relevant factors into account. In open-loop operation, pneumatic cylinders offer both the moving and the holding function, even if they are not required. By contrast, an electric drive only offers the holding function if it is necessary, but requires additional energy to do so. If the two drive concepts are to be compared to one another in a meaningful way, they must offer the same functions with the same parameters.

4 Energy efficiency in pneumatics

4

Measures for increasing energy efficiency are presented below, both for pneumatic and for electric functional chains. In compressed air systems, the functional chain consists of compressed air generation, compressed air preparation, compressed air distribution and the application. Chapter 6 contains an overview of all measures described.

Each measure is described briefly in this chapter, and then evaluated. The evaluation will be presented in the same format, which is introduced below.

Evaluation of the measures

Action	★★★
Relevance Relevance in industries or specific areas	**Expense** Description of the expense for implementing the measure
Applicability **X%**	**Saving up to** **X%**

The **relevance** indicates those areas, industries or typical applications where the measure can often be used particularly well, or in which they are particularly effective.

The **expense** always refers to an existing system. For new installations, all measures presented can be implemented at a far lower cost.

Applicability provides a percentage figure, based on experience, for the cases in which it makes sense to implement the measure.

Savings indicates the maximum percentage of the energy consumption which can be saved by the measure. The value always refers to the actual air consumption in the respective object studied and therefore cannot be transferred to the total energy consumption of the system or added to other measures.

Stars compare the benefit to the expense, and provide a summary evaluation for the measure.

All figures and calculations for the measures presented are either based on studies, or reflect the experience of the project partners. None of these values can be transferred directly to a company, as the information in this paper is based on an average company. Tests are always required in individual cases.

The percentage savings with the measures presented in pneumatics and electric drive and handling technology cannot, as mentioned earlier, be compared directly with one another, as they are based on different parameters.

The evaluation focuses on existing systems. For new systems, the expense is generally lower, and the applicability higher, so that the measures for increasing energy efficiency in new systems are generally amortised very quickly.

All measures presented make sense when considered separately. However, the overall system must always be taken into account. For example, some measures are mutually exclusive. In efficiently sized drives, a general reduction of the operating pressure leads to disturbances in operation. By contrast, a pressure reduction in oversized drives can be a simple and appropriate measure. Even if an excessive pressure/pressure range was selected as a redundant safety precaution, a general pressure drop can save energy without leading to performance deteriorations. Therefore, the overall system from compressed air generation to the application must always be considered.

4.1 Provision of compressed air | compressors

Compressors are powered by electricity and generate compressed air. They form the heart of a compressed air system. 70% of the overall costs of a compressor system relate to energy. They therefore have a major influence on the economy of the system. There are different types of compressors; their use depends on pressure level, delivery rate, switching frequency and utilisation requirements. Comprehensive planning (design and selection) of the compressor station, and the use of a modern and intelligent integrated control unit can save a significant proportion of the energy used. Due to thermodynamics, a large amount of heat is produced during the compression process. It can be recovered centrally at the compressor station via heat exchangers and put to good use. For example, waste heat can be used for heating rooms or water, which saves heating energy elsewhere, and increases the energy efficiency of the entire production system.

4.1.1 Demand-based compressor design using an integrated control unit

Industrial systems with a high degree of automation consume a relatively large amount of compressed air, which fluctuates cyclically with the production process. Breaking down the consumption into base, medium and peak load consumption is a first step to selecting suitable compressors. The effectiveness of an integrated control unit depends on the graduation of the compressors' delivery rates. It is easier to combine several small compressors than two large machines in order to follow the dynamic consumption profile. That minimises idle times for the speed-controlled screw compressors that are frequently used and is a simple way of saving energy. The station's pressure range can be reduced and the regulating pressure of the station can be decreased.

Compressor design and integrated control unit	★★★
Relevance In companies with a dynamic consumption profile (breakdown into base, medium and peak load possible)	**Expense** Separate installation of the integrated control unit
Applicability **20%**	**Saving up to** **20%**

4.1.2 Central heat recovery

To compress the ambient atmosphere drawn in, it is compressed to a higher pressure level. At the same time, this process increases the temperature. Like a heat pump, the compression allows heat from the drawn-in compressed air to be used. It can be dissipated via a heat exchanger and put to good use.

The compressor station is a central system, which means that the waste heat is largely produced centrally. Relatively few devices are required to recover the heat efficiently. The heat can be used as heating air, to heat water or cool the production hall, which saves the energy used for heat generation elsewhere. Heat exchangers can be retrofitted to the compressors. If the high potential savings are to be used appropriately when planning new or redesigning compressor stations from an energy perspective, heat recovery must always be considered. In dry-running compressors, up to 96% of the heat can be recovered for hot water, and in oil-lubricated compressors, up to 76% can be recovered (up to 96% if exhaust air is used).

Comment and evaluation:
Up to 96% of the heat created when compressing the ambient air can be recovered. While that does not reduce the energy consumption of the compressor, it allows the recovered energy to be used as heat in other areas, thus saving energy there.

4.1.3 Use of speed-controlled compressors

In practice, many believe that using speed-controlled compressors is the means to the end in energy saving. Speed-controlled compressors adapt their speed to a range between 20% and 100% of the required energy; the optimal working level with minimum power consumption is 40–70%. When operating outside this range, the power consumption increases as a quadratic function, which is why speed-controlled machines should be used as peak load compressors at the point of operation. In general, a single speed-controlled compressor in the network is sufficient.

Central waste heat recovery	★★★
Relevance In all companies in which the heat generated can be used	**Expense** The heat recovery system is installed at the compressor station. The heat must be supplied to other processes.
Applicability **50%**	**Additional benefit up to** **96%**

Speed-controlled compressors	★★
Relevance For all companies with fluctuating peak load consumption	**Expense** Speed control is incorporated during system planning. Retrofitting is not recommended.
Applicability **25%**	**Saving up to** **15%**

4.1.4 Lowering the system pressure

Rough calculations show that reducing the regulating pressure at the compressor – where possible – results in an energy saving of up to 10% per 1 bar of pressure reduced. In conjunction with a decrease in system pressure, the effects on the remainder of the compressed air system, which will be explained below, should be considered.

In most cases, the pressure is regulated to a lower level before application via a pressure regulator. If this is the case for every system, the overall system pressure should be reduced at the compressor, and the pressure regulators should be adjusted accordingly. A constant system pressure at the pressure level actually required can be achieved via an intelligent compressor station, which prevents excessive compression.

In existing systems, pneumatic drives are often oversized and consume more energy than required for their function. In this instance, the pressure level can be reduced without impairing the function. The minimum pressure required must be tested individually on every machine. However, it should be noted that a general pressure decrease in a system with energy-efficiently designed drives results in performance deteriorations, and thus can cause disturbances in operation. An intelligent compressor control system, combined with efficiently designed drives is preferable to a general pressure decrease.

Lowering the system pressure	★★
Relevance In systems in which all pneumatic drives are oversized	**Expense** Pressure reduction at the compressor
Applicability **50%**	**Saving up to** **15%**

Optimisation approach

Design of compressor stations

The EnEffAH project developed a tool for the optimal design of compressor stations.
An empirical process is used to determine and select the ideal configuration for a compressor station from a number of different compressors (pressure level and delivery rate range). The starting point is the consumption profile of the compressed air system, which is broken down into base, medium and peak load. The compressors identified by the algorithm adapt to the different consumption levels thanks to being flexible in combination as well as having minimal power consumption. The algorithm underlines the current trend for graduated use of multiple small compressors.

4.2 Compressed air preparation

The air preparation unit in modern compressed air systems is located between the compressor and central reservoir. The compressed air quality classes per DIN ISO 8573-1 (2010) make it easier for users to define their requirements and select the preparation components. The VDMA Standard Sheet 15390 suggests suitable compressed air qualities for different applications. Compressed air quality depends on the residual oil content in the air, the sizes of the dirt particles, the density of solid particles and the water content or pressure dew point depending on the air pressure.

4.2.1 Drying compressed air

An air dryer downstream of the compressor dries the compressed air. There are a variety of drying systems available. The most common processes are condensation, diffusion, absorption and adsorption. Each drying method has its specific advantages for various applications. Modern and efficient air dryers, some of which are hybrid systems which combine the advantages of different drying methods, allow up to 70% of the energy used for drying to be saved. Different applications and industries require specific drying technologies, each of which needs very different amounts of energy. While refrigeration dryers only require roughly 2% of the overall energy required to provide the compressed air, adsorption dryers (special applications) require up to 30%. Accordingly, the potential savings depend on the technology used.

Drying compressed air (refrigeration drying)	★
Relevance In all systems in which refrigeration dryers are used	**Expense** An existing air dryer must be replaced by a more efficient air dryer
Applicability 60%	**Savings of up to 2%**

Drying compressed air (adsorption drying)	★★
Relevance In all systems in which adsorption refrigeration dryers are used	**Expense** An existing air dryer must be be replaced by a more efficient air dryer
Applicability 10%	**Saving up to 20%**

4.2.2 Designing the compressed air preparation unit

In medical applications and the food sector, the demands on compressed air quality are high. Manufacturers can specify the required compressed air quality for individual components. The range of applications in which these components are used then determines whether a higher class, and thus additional preparation is needed. The pressure drop across the filters increases with higher purity requirements.

If the quality requirements defined for the compressed air preparation systems are too high, this often results in oversizing of the drying and filtering systems. Every component in the compressed air preparation system is a resistor and causes a certain pressure drop in the flow. Filtering is therefore to be designed according to the principle: as much filtering as needed, as little filtering as possible. Correctly maintained filters have a pressure drop of 0.1 to 0.2 bar. In soiled filter systems this value can be far higher, which is why regular maintenance intervals must be complied with strictly.

Design of the compressed air preparation system ★★	
Relevance In all systems with compressed air pre-paration. The compres-sed air quailty selected is often too high.	**Expense** Correct selection of the compressed air quality via a suitable com-pressed air preparation system
Applicability 20%	**Savings of up to 10%**

4.2.3 Regular maintenance for reducting pressure drops

Regular maintenance of the preparation components is the key to ensuring that the complete system operates very efficiently. Filters wear down or become clogged, which results in a large pressure drop (often up to 0.5 bar). In practice, there are often multiple clogged filters and preparation components back to back. To compensate for this, pressure is increased at the compressor without remedying the real cause. With a 10% energy saving per 1 bar of pressure at the processor, regular maintenance (continuous maintenance and replacement of the components) permits a high potential efficiency.

Regular maintenance of compressed air preparation systems ★★★	
Relevance Many systems do not work properly due to incorrect design. The compressed air quality selected is often too high.	**Expense** Maintenance of the compressed air preparation system in accordance with the specifications of the preparation unit
Applicability 80%	**Savings of up to 20%**

Comment and evaluation:
In practice, rarely or incorrectly maintained or even clogged compressed air preparation units can increase the pressure drop by over 2 bar. If it is reduced, up to 20% of energy can be saved.

4.3 Compressed air distribution in the piping system

After the compressed air preparation, the air is distributed to the entire production area, up to the service unit on the consumer. The pneumatic distribution system is generally a welded or clamped network (stainless steel, plastic, copper or aluminium), which should ideally be leak-free. The pipe material in particular should not have a negative effect on the compressed air quality at the consumer. On average, only 10% of the leaks in the entire functional chain occur in the distribution network. Various designs, from ring lines to star lines, guarantee efficient and effective air distribution. Planning a compressed air system includes multiple aspects, e.g. network expansion, maximum load capacity of the pressure level and flow, future capacities and installation costs.
As the network is rarely changed retrospectively, the measures for increasing energy efficiency primarily refer to the planning and design of the network. If leakages are present in the network, they must be remedied quickly, as large amounts of compressed air can escape.

4.3.1 Optimal sizing of piping

Physically, there are no compressed air systems without pressure drops, as air can only flow through pipes if there is a differential pressure. The extent of the pressure drop in the pipe system is far higher in reality than is theoretically necessary. This is due to incorrect installation and excessively narrow flow cross sections or frequent cross section changes. Compressed air pipes are often laid similarly to water pipes and electricity cables without an understanding of compressed air as an energy medium. Oversizing the pipes so the pressure drops are kept to a minimum is a simple solution. That means that there is a large amount of air in the network, which does not generate increased costs (except a one-off filling), and can also cushion consumption peaks to a certain extent. If the compressed air system is designed specifically so that the pipes are not only used to transport the air, but also as a storage element, it is referred to as a storage network.

A storage network has several disadvantages and thus designing a network as a storage network is not recommended. (*See the* “**Optimisation approach**” *below*)

Optimal sizing of piping ★★	
Relevance In all systems which are extended or newly installed systems	**Expense** Optimal design of the pipes using design tools before installing the network
Applicability **20%**	**Saving up to** **10%**

4.3.2 Optimising the system infrastructure

In addition to pipe size, the network infrastructure plays an important role, for both ring and branch lines. Branch lines feature a continuous pressure drop from the generator to the distributor, and the network results in a type of tree structure. Ring lines offer the advantage that the pressure can be distributed evenly through closed line circuits.
The distribution lines in a network is often designed as a ring line, and the main and connecting lines are designed as branch lines. However, what makes a theoretically ideal network, and what statements can be derived from it? To answer this question, the EnEffAH project developed the prototype of a tool for simulating and optimising the ideal network infrastructure.
(*See the* “**Optimisation approach**” *below*)

Optimisation of the network infrastructure ★	
Relevance In all systems which are refurbished or extended, or in new installations	**Expense** Recording consumption data, creation of a network diagram, cost analysis, calculation of the pressure drops
Applicability **40%**	**Savings of up to** **5%**

4.3.3 Sturdiness and positioning of buffer storage

If a compressed air network is designed as a distribution network only, decentralised buffers can be used in specific positions. In particular in the immediate vicinity of systems with highly fluctuating consumption or high consumption peaks, a buffer can have a smoothing effect on the consumption.
In the best case, the compressor station can be designed for a lower peak load. Lower power reserves are required, which has a positive effect on the energy efficiency.
(*See the* "**Optimisation approach**" *below)*

Sturdiness and positioning of buffer storage ★★	
Relevance In all companies in which sporadically high consumption leads to pressure drops	**Expense** Installation of buffers in compressed air systems
Applicability **40%**	**Savings of up to** **10%**

4.3.4 Reduction and elimination of leakages in the main system

In a compressed air system, a total of up to 30% of the compressed air is often lost due to leakages. Leakages occur during compressed air distribution (main network) and at the application (see Chapter 4.4). Leakages in the main network are rare and only account for a minor portion of the total leakages. The main network can normally be kept virtually leakage-free. Preventive measures for this include the selection of the right piping material, proper installation and training of employees in handling compressed air and leakages.

An existing leakage in the compressed air network is either determined via a compressed air audit, the switching characteristics of the compressors or the pressure drop in the reservoir by switching off all compressed air consumers. If the number of leakages exceed a certain threshold value, they should be located and eliminated if it is economical to do so.

Elimination of leakages in the network ★★★	
Relevance In all companies where the compressed air network is not leakage-free	**Expense** A team of experts studies the system and specifies measures. Regular measure to ensure success
Applicability **80%**	**Savings up to** **5%**

Optimisation approach

Prototype tools for network design

The EnEffAH project developed prototypes of various tools for designing, dimensioning, optimising and analysing the sturdiness of compressed air piping systems. The approaches are presented below.

Optimised pipe dimensioning
The tool which was developed and implemented helps planners of compressed air systems determine the optimal pipe diameter. The planner specifies the pre-defined structure of the network and defines the maximum amount of air required for every consumer. The dynamics of the compressor station are not considered, and is assumed to be a source with constant pressure. The tool uses a model-based optimisation method to calculate the diameter of the individual pipes. For practical reasons, the number of pipe diameters which can be selected is restricted, as only graded and standardised diameters can be purchased from authorised dealers. “Model-based” means that the compressed air system is described at an abstract level using mathematical correlations. For example, pipe fittings are added to individual pipelines as equivalent lengths, and not considered separately. The statistical network model is used to calculate the pressure drop from the generator to the respective consumers. The optimiser from the class of genetic algorithms repeats the network configuration until it meets the requirements of the compressed air system. The requirements primarily consist of maintaining the maximum permitted pressure drops between generation and consumer.

A minimum pressure drop throughout the entire network is often a target. If there are no other requirements, the diameter selected is often the maximum permitted diameter. This means that the installation costs need to be considered in addition to the pressure requirements. A clever combination of these two criteria leads to an optimal distribution system without unnecessary storage capacities. Finally, note that the selection of the pipe diameter depends on the placement of the individual consumers. As a result, the local consumption distribution is closely linked to the optimisation result.

Optimising the system infrastructure
For computer-aided optimisation of the network infrastructure, the tool is supplemented with a pipe sizing option. Based on a statistical network model, an additional degree of freedom is introduced for optimisation. The list of permitted pipe diameters is supplemented by diameter 0, i.e. the case “No pipe”. Based on a maximum possible network configuration (where can pipes be routed?), the optimiser is free to decide which pipelines are considered important and which diameter should be selected. As the optimisation process is a purely mathematical algorithm with limited intelligence, the requirements must be selected so that it results in network configurations that can be implemented in practice. However, statements, e.g. on potential bottlenecks, can already be deduced from the theoretically permitted network configurations. In addition to the requirement of a minimum pressure drop across the network, the balance of the pressure through the network is also considered.

...

Sturdiness analysis of the network and positioning of buffers

Optimised positioning of decentralised buffers increases the sturdiness of a compressed air system. Compressed air systems are not sturdy or sensitive if occasional consumers of large amounts of air influence the pressure throughout the network, and thus they also adversely affect the switching characteristics of the compressor station.

If consumers with highly fluctuating demand profiles are connected to the compressed air system via branch lines, buffers are positioned upstream of these consumers. In high density networks with ring lines, the positioning of the reservoirs is supported via the new design algorithm. The sturdiness is investigated via a dynamic network model and a theoretical system concept for sensitivity analysis. The network structure and the pipe diameter are specified. A genetic algorithm, which can can set the volume upstream of every consumer, is used as an optimisation process (the permitted volume is specified in advance with the degree of freedom “No volume”).

The optimisation results clearly show the weaknesses in the network. Please note that similar to line dimensioning, the positioning of the buffers depends on the position of the consumers in the network.

4.4 Application

The application is the last point of the pneumatic functional chain and the compressed air distribution system. It consists of a local air preparation system (decentralised filtering, pressure regulation, etc.), a compressed air distribution system (generally via tubing lines), valves, pneumatic drives or other components in the application.

This paper only considers the compressed air range which is relevant for drive and handling technology. Compressed air guns, functional air (like sealing air) or pneumatic tools, which also use much compressed air are not considered in any great detail. However, as they consume a considerable amount of compressed air consumption, they should always be incorporated in efficiency considerations.

4.4.1 Correct design of the drives | Avoiding oversizing

Pneumatic drives are often oversized and the drive force is generally far greater than would actually be necessary for the application. Potential reasons for this are that a larger cylinder is used for safety reasons, although a smaller size would offer the necessary functionality. Another reason could be that having fewer sizes reduces the range of part numbers and thus saves costs. Experience shows that in an application-specific, energy-efficient design on average half of all the drives can be one size smaller.

Correct design of drives and components	★★★
Relevance In all industry & areas, in particular where only few cylinder sizes can be used due to the warehousing costs	**Expense** Correct design of components without exaggerated safety factors
Applicability **80%**	**Savings up to** **40%**

Comment and evaluation:
The saving cannot be transferred to the total compressed air consumption, as only roughly 20% of the total compressed air is used by the pneumatic drives. Savings only ever refer to the actual air consumption of the respective application.

4.4.2 Avoiding dead volume | Reducing tubing volume

In particular in bigger systems there are often large distances between the valves and cylinders, for example when the valves and valve terminals are installed centrally in a control cabinet. The tubes connecting them represent a dead volume for every switching operation, as they must be filled and emptied every time. The compressed air needed for this is lost unused. It is therefore essential to minimise dead volumes between the cylinder and valve, e.g. by shortening distances or using smaller diameters. However, the tubing diameter should not drop below a certain amount, as otherwise flow resistances increase and the dynamics of the drives suffer. The ideal balance must be determined when designing each individual system.

Avoiding dead volume ★★	
Relevance In areas where many central valve terminals are used, in particular with many small cylinders and frequent switching	**Expense** Valves must be positioned as close as possible to the cylinder
Applicability **30%**	**Saving up to** **20%**

Comment and evaluation:
In general, 30% of compressed air for operating pneumatic drives is used to fill dead volume in the tubing. The remaining 70% reaches the pneumatic cylinders. On average, the dead volume can be reduced by roughly 60%. This results in a saving of roughly 20%. Savings only ever refer to the actual air consumption of the respective application.

4.4.3 Leakage detection and elimination

Even the best maintained compressed air systems are subject to leakages as they can never be avoided entirely (a well-maintained compressed air system has leakages of between 8% and 10%). In spite of this, leakages offer an important opportunity to increase the energy efficiency of a compressed air system. In an average system, up to 30% of the compressed air is lost through leakages. In addition to the leakages in the main network (see Chapter 4.3.4), the majority of the leakages are to be found in the system itself. Major leakages are generally easy to detect and remedy, but most small leakages (especially in the systems), which are responsible for the largest losses overall, can only be found by experts with special devices for locating leakages and defining measures to eliminate them.

By installing a condition monitoring system, the air consumption system can be monitored continuously. This allows changes to consumption due to increasing leakages to be detected and eliminated at an early stage.

Leakage detection and elimination (system / application) ★★★	
Relevance In all industries & areas	**Expense** A team of experts studies the system and specifies measures. Poss. condition monitoring system for continuous monitoring
Applicability **70%**	**Saving up to** **20%**

Comment and evaluation:
An average system has a leakage value of 30%. This can be reduced economically to approx. 10%. This means that savings of up to 20% can be made.

4.4.4 Operating strategies

In standard pneumatics, the drive chambers of pneumatic cylinders are generally pressurised with supply pressure via switching valves and completely filled or emptied for each movement. The dynamics required can be set individually via exhaust air flow control. In most cases, the air consumption is relatively high and largely independent of load or dynamics, as the drive chamber is always completely pressurised with supply pressure. As a result, the two functions, moving and holding the load with high force in the end position (see also Chapter 3.2), are performed simultaneously, although in many cases both functions are not required. Depending on the load and function required, suitable control and operating strategies permit far lower consumption than in standard operation.

4.4.4.1 Single-acting cylinders

In many applications, only one direction (e.g. the forward stroke) of the cylinder is time-critical or productive, while the stroke in the other direction could take longer and be performed with less drive force. The simplest way of utilising this potential is to use single-acting cylinders, which are returned to the initial position via spring return. Only the forward movement must be performed under pressure, allowing the retraction process to be implemented without consuming compressed air. However, this restricts the maximum stroke length. Besides saving compressed air, this means that a simpler valve can be used, or only one valve can be used instead of two.

Single-acting cylinder	★★
Relevance For non-time critical processes, short strokes and when high drive forces are only required in one direction	**Expense** Use of corresponding components
Applicability **10%**	**Savings up to** **50%**

Comment and evaluation:
A single-acting cylinder allows an almost 50% reduction in the compressed air used. Savings only ever refer to the actual air consumption of the respective application.

4.4.4.2 Using a short circuit valve

The two cylinder chambers can be connected to one another via an integrated 2/2 short-circuit valve, in addition to air inlet and exhaust valves, to enable part of the compressed air to be fed back from one chamber to the other. Depending on the application, the short-circuit valve can be used differently.

If a cylinder with a piston rod is used, the short-circuit valve can be opened throughout the entire movement, at least for the forward movement. It compensates the pressure between the two cylinder chambers. Although the pressure in both chambers is the same, the effective piston rod area on the exhaust chamber side is reduced and the cylinder moves forward. In addition to the short-circuit valve, the exhaust valve can also be opened during the movement, in which case the supply network only requires an operating volume equal to the volume of the piston rod. The valve is not required to have a closed position, which means that a standard 5/2 valve is sufficient. With a double stroke in this type of actuation, the compressed air required can be reduced by up to 43%; however, as a result of the lower drive force produced, the dynamics must be expected to deteriorate.

The short-circuit valve for vertically installed cylinders functions slightly differently. It is activated during movements from top to bottom, while the air supply is switched off at the same time, so that the movement is generated by gravitational force and no compressed air is required.

Short-circuit valve	★★
Relevance For non-time critical processes or vertically operated drives	**Expense** The additional valve must be integrated in the control sequence
Applicability **10%**	**Savings up to** **43%**

Comment and evaluation:
Energy savings of up to 43% can be made using a short-circuit valve. Savings only ever refer to the actual air consumption of the respective application.

4.4.4.3 Supply air flow control and deliberate deactivation

If the focus of the application is on the movement function, the supply flow to the drive chambers can be interrupted after the movement is complete. This prevents additional pressurisation of the drive chambers after completion of the movement, which is unnecessary in this case.

In most applications, cylinders are operated via a 5/2 valve. As a result, the movement is not pre-exhausted. If exhaust air flow control valves are used to regulate the movement dynamics, the average pressure in both cylinder chambers during the movement is relatively high. As a result, the savings effect due to deliberate deactivation is relatively low. If the movement of the cylinder is regulated via supply air flow controls instead, the average pressure decreases sharply during the movement. If the 5/2 valve is replaced with a 5/3 valve, which is closed in the neutral position, a relatively low pressure level can be maintained in the cylinder after the movement has occurred, preventing the unintentional re-pressurising of the drive chambers. Simulations of the movement dynamics of the cylinder show that this measure can save up to 70% compared with standard operation, depending on the load, with the same movement time. Lab tests prove these results. Depending on the load and the degree of oversizing, an average saving of 50% can be assumed.

A major advantage of this method is that the system does not have to be readjusted on load changes, as the air-saving procedure does not occur until the movement is completed. If the system load changes, a higher pressure level is formed in the drive chamber during the movement and the saving effect is reduced accordingly. The application functions without further measures.
The use of supply air flow controls has a negative effect on the movement properties, as the stick-clip effect can cause unevenness during the movement depending on the load. In individual cases, this can result in notably jerking movements. If this interferes with the application, a compromise must be found between supply air and exhaust air flow control.

Supply air flow control and deliberate deactivation	★★
Relevance For highly oversized, large drives, or in applications with changing loads	**Expense** Use of a 5/3 way valve, supply air flow control instead of exhaust air flow control
Applicability **30%**	**Savings up to** **50%**

Comment and evaluation:
This measure allows up to 50% of the compressed air actually used to be saved in the respective application in a normal operating case. The saving cannot be transferred to the total compressed air consumption, as only roughly 20% of the total compressed air is used by the pneumatic drives.

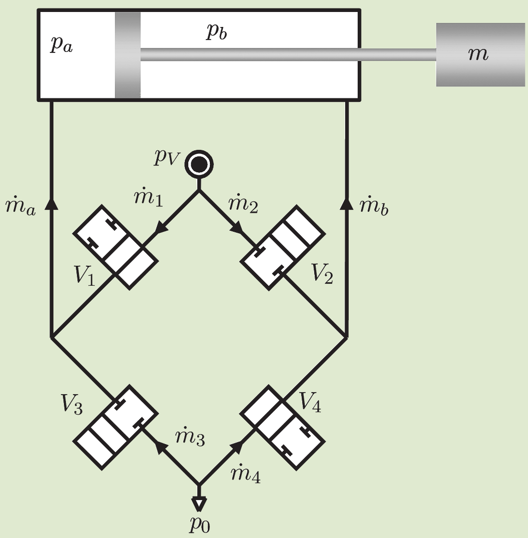
Optimisation approach

Use of the expansion energy via optimised valve control

The EnEffAH project developed operating strategies for energy-efficient movement, which can use the expansion energy present in the compressed air. In this operating mode, the focus is on movement functionality. In contrast to the strategies considered to date, this type of circuitry does not require any flow control valves. The required speed is achieved via targeted activation and deactivation of the individual valves during the movement process. A bridge circuit is used which consists of four 2/2-way valves. The full supply pressure is exploited for maximum movement dynamics, which avoids the stick-slip problems (see 4.4.4.3). If the exhaust valve is deactivated during the movement so that the compressed air sealed in the drive chamber is depressurised, the expansion energy stored in the compressed air is utilised, in contrast to the other strategies.

Depending on the parameters defined (especially the end position force) up to 85% of the compressed air can be saved compared with standard pneumatics. However, this means that the holding function is no longer totally available in the end position. This is a theoretical limit value, as the system is susceptible to other malfunctions (e.g. external forces or changes in friction). If the holding function is required, it can be achieved via a clamping cartridge or a terminal block with end-position locking, for example. If the control of the valves is changed so that a higher end position pressure is achieved, the savings effect decreases, but the system sturdiness increases.

At an end position pressure of 2.5 bar, the savings effect is roughly 65%. This end position pressure is sufficient for most applications, depending on the cylinder. This also implements the holding function.



The individual valves are controlled based on optimisation. Using a mathematical system model in conjunction with numerical optimisation models enables an energy-efficient control with simultaneous reduction of the end position speed. The maximum permitted speed on impact in the end position can be taken into consideration in the optimisation algorithm. That eliminates the need to absorb the excess energy in the end position via expensive shock absorbers. As the end position speed is a major aspect of designing pneumatic drives, this also affects the sizing of the cylinder, and can lead to further savings if the design is changed. However, a disadvantage of this method is a more complex valve structure.

In summary, the advantages and disadvantages are as follows:

Advantages	Disadvantages
• High savings potential (use of expansion energy) • Reduced adjustable end position pressure • Utilisation of the full supply pressure for high movement dynamics • Reduction of the end position speed • No shock absorbers required	• Increased hardware expenses • Control technology expenses • Susceptibility to external influences

Optimised valve control ★★	
Relevance For large drives with-out or with low holding force requirements	**Expense** Adaptation of the valve structure, control system
Applicability 30%	**Savings up to 65%**

Comment and evaluation:
Using the expansion energy, up to 65% of the compressed air used by the application can be saved. The saving cannot be transferred to the total compressed air consumption, as only roughly 20% of the total compressed air is used by the pneumatic drives.

4.5 Services

The trend in increasing energy prices is forcing users of compressed air systems to overcome new challenges. In order to guarantee the long-term viability of compressed air systems, it makes sense to involve an expert – a manufacturer or service provider – in the operational phase. The focus should not only be on the power costs; a cost study for the entire product life cycle must always be carried out. Expert knowledge allows the efficiency potential to be utilised, thus reducing the Total Cost of Ownership (TCO) or the life cycle costs.

The technical measures presented in the previous sections can help to increase the energy efficiency in all areas of the compressed air system. However, these measures are often not implemented because of constraints. The measures do not need to be implemented in-house, as many of them are also offered by external service providers. Creating an awareness of the high energy saving potential in compressed air systems is particularly important, as is the knowledge that energy saving measures are advisable. If this is the case, a suitable offer can be found in four steps.

System analysis
Before selecting specific efficiency measures, it can be advisable to obtain an overview of the condition of the compressed air system via a compressed air audit. Aspects such as system design, maintenance condition, pressure level and leakage rates in the various parts of the system are analysed.

Identification of energy-saving potential
The objective of the system analysis is to identify the economic potential that can be achieved using specially targeted services. If the targets are clearly defined, the measures to be implemented can be selected based on the result of the compressed air audit. It often makes sense to combine various savings concepts with one another to maximise the potential. The proposed efficiency measures do not always lead to energy savings, but can have other positive side effects. For example, these can be a well-maintained system, a reliable supply of compressed air or a refurbished system.

Identification of alternative business model and evaluation
Once the measures have been identified, the type of implementation must be chosen. Is the measure to be performed completely independently, or commissioned by an external service provider? It is possible to create intermediate setups, in which individual process steps are performed by the company and others are outsourced to an expert. The specific procedure can depend on whether the company has the expertise required to implement the measure or partial step and a sufficient budget for the investments required.

Implementation

There are a number of companies that provide energy saving services. In the area of drive and handling technology, they can be carried out by manufacturers of pneumatic components or machine manufacturers, as well as by specialised service providers, who do not produce products themselves, and can therefore offer independent solutions. Higher up in the compressed air generation sector are the compressor manufacturers and power supply companies as potential service providers. These services are also known as compressed air contracting.

Economic assessment

Before using any service to reduce energy consumption the economic viability of the service has to be evaluated. The cost reductions made possible by the energy saving measures must be calculated as part of a life cycle-oriented calculation of production costs, and a decision must be made as to whether they are sufficient to at least compensate for the resulting additional costs. Evaluation using multiple scenarios can contribute to providing the broadest possible base for a preliminary evaluation.

Optimisation approach

Evaluation of business model configurations for leakage management

The EnEffAH project evaluated a range of configurations of leakage management in terms of their economic viability, the potential energy savings and additional risks and market effects: without sensors, with sensors, using a service provider only, cooperation between a service provider and the customer, payment according to expense, according to the energy saving achieved or a fixed rate.

In companies with a large system and average leakage rates, all variants proved beneficial compared to not taking any action.

5 Energy efficiency of electric drives

5

This chapter describes measures for increasing the energy efficiency of electric drive systems. The measures are broken down into two sections. The first section discusses energy provision and distribution, which offers little potential for optimisation compared with pneumatics. The second section presents measures for drives and applications. Planning and design play an important role here, as the measures there have a particularly strong effect on energy consumption. Finally, measures which can be used when commissioning new drives or optimising existing applications are described.

The applicability and potential savings of each measure are not transferrable to all drives, as there are many different influencing factors and requirements. Also, the components and measures cannot be considered separately, as they often depend on one another. It therefore makes sense for all measures to use design software tools to simulate the complete drive system. This allows losses to be localised and the measures to be evaluated in terms of their potential. That cannot be done without precise simulation models, which map the system characteristics and losses correctly.

5.1 Energy provision and distribution

Compared with pneumatics, energy provision is far simpler. Power is primarily generated by an external power supply company, and the industrial company only has to ensure that it is distributed within the building. This is done via a low voltage electrical installation (400/230 V). Some of the electricity is lost during distribution to the sockets or terminals because of the resistance of the cables. These resistances lead to voltage drops along the cables. Under the valid DIN or VDE regulations, installations are designed for a maximum voltage drop of 3% at maximum network load. As a result, the losses in distributing electric energy are low. The electric distribution network can be assumed to have an approximate efficiency value of over 97%.

Some electric drive systems may also require an additional or exclusive low voltage direct current supply at 24 V, for example. This is generated decentrally by small power supply units. Current switched-mode power supplies for these applications have efficiencies ranging between 70% and 95%.

5.1 Energy provision and distribution

5.1.1 Optimising low voltage direct current supply

If several drive systems require a low voltage direct current supply, this should be supplied via a shared power supply unit, as power supply units with higher rated capacities are generally more efficient. Using modern switched-mode power supplies lead to further efficiency increases. Power supply units do not have to be rated to the precise wattage, as the efficiency is generally very high, even in the partial load range.

Optimising low voltage direct current supply	★
Relevance Where many drive systems can use the same power supply and inefficient power supply units are used	**Expense** Exchanging an existing power supply unit or selecting particularly efficient power supply units for new systems
Applicability 10%	**Savings up to** 2%

5.1.2 Reducing energy consumption in standby mode

Electric drive systems also draw electric power in standby mode. This is particularly relevant during breaks in production, which can last between a few minutes and several days. Energy savings are maximised if the power supply is switched off completely during breaks. Alternatively, components can be set to an energy-saving state, if the software and hardware support this. The commands for energy-saving statuses are already partially integrated in some fieldbus systems. Possible difficulties during the start-up of devices may prevent them from being deactivated or switched to the energy-saving mode. This is why the start-up process should be as automated as possible so that it is as reproducible and reliable as possible.

Reducing energy consumption in standby mode	★★
Relevance Wherever electric drive systems are not switched off in breaks	**Expense** Adding deactivation options to existing systems, using corresponding components to new systems
Applicability 20%	**Savings of up to** 5%

5.2 Drives and application

Planning and design

Planning and design are essential for electric drive systems, as these stages offer the highest energy savings. Precise knowledge of the application and the parameters are required to design an energy-efficient system. The more accurately the required movement, the load to be moved, external forces and other conditions are known, the easier it is to find the optimal drive system.

5.2.1 Using low-friction mechanical components

Losses in mechanical components are largely due to friction. Therefore components with minimum friction should be used. That applies to linear axes, guides and to any gear units.

Example:
A linear movement of 0.4 m with a load of 5 kg in one second can be achieved with a variety of drive systems. The project compared three drive systems for this movement. A toothed belt axis driven directly by a motor consumed an average electric power of 35.5 W. The same toothed belt axis driven by a motor with gears consumed 44.4 W (+25%) and a comparable spindle axis required 91.61 W (+158%). Friction had the greatest impact on the widely varying energy efficiency. This clearly shows that the choice of mechanical components is crucial.

Using low-friction mechanical components	★★★
Relevance For all applications which offer various implementation options	**Expense** Comparison of friction in the design
Applicability **10%**	**Savings up to** **20%**

5.2.2 Minimising moving masses

In addition to the effective load, i.e. the load which the application must move, some of the mechanical parts of the drive system must be accelerated and braked. Each acceleration and braking process requires energy. The greater the moving mass, the greater the amount of energy used. It therefore makes sense to minimise the moving mass. This can be done by using lightweight components, and by ensuring that the axes are no larger than necessary. Oversizing increases the moving mass and causes unnecessary losses.

For multi-axis systems with multidimensional movements, it is particularly important that moving masses be minimised. In Cartesian three-dimensional gantries, up to two linear units must be moved by a third. These masses can greatly exceed the effective load to be moved in pick & place applications. The potential for saving here is great, as using lightweight components or optimised arrangements such as delta kinematics/ tripods or H-type gantries with recirculating belts can greatly reduce the moving masses.

Minimising moving masses	★★★
Relevance For dynamic movements, especially for multidimensional drive systems	**Expense** Comparison of the moving masses in the design
Applicability **10%**	**Savings up to** **15%**

5.2.3 Avoiding oversizing

Oversizing drive components of any kind generally results in excessively high power consumption. If the design chain includes the mechanical system as well as the motor and the servo controller, safety factors are often incorporated at each step, resulting in a highly oversized motor and servo controller overall. Systems which are 50 to 100% oversized are not rare. These components often operate at non-optimal levels, and require more energy than actually necessary. Also, the number of oversized components leads to a disproportionately heavy moving mass, which also increases the energy consumption.

All components must be designed using a common sizing software. If the movement requirements are known precisely, all components can be selected accordingly, avoiding oversizing.

Avoiding oversizing ★★	
Relevance Cylinder design incorporating excessive safety factors	**Expense** Designing all components using suitable software tools
Applicability **50%**	**Savings up to** **10%**

5.2.4 Optimising energy consumption in breaks in movement

The periodic movement breaks in inching operation must be considered separately from the movement itself. If a force must be applied in the movement breaks, or the position must be held actively, the energy consumption in these breaks must also be examined. The position can be held via the motor, using a holding brake or a mechanical automatic locking system. No general statement can be made as to which option is optimal. Each case must be assessed individually as to which parameters and options result in the lowest possible energy consumption. The longer the breaks in movement compared to the movement, and the higher the forces to be applied, the more optimisation makes sense. Using automatic locking mechanisms can conflict with the measure of using low-friction components. This must also be considered on an individual basis.

Optimising energy consumption in breaks in movement ★★	
Relevance For long movement breaks compared with the movement times and when a holding force is required in the end position	**Expense** Comparison of the energy consumption in movement breaks
Applicability **10%**	**Savings up to** **4%**

5.2.5 Use of efficient motors

Selecting the right motor can increase the energy efficiency. However, it is often impossible to make an evaluation and selection based on data sheet specifications, as no information on the energy characteristics of the components is available. Sizing is largely based on torque and speed requirements, but the losses which occur in operation are not easy to determine. The energy efficiency of motors with efficiency ratings can only be compared objectively under stationary continuous operation. No general rate of efficiency can be specified for non-stationary movements (inching operation), which are common in handling technology. If this is the case, the rate of efficiency specified on the data sheet should only be used as a guideline when comparing the energy efficiency of similar motors.

Permanently excited synchronous machines are ideal for a variety of applications, as they have low losses for a large operating range. If a motor can be used as a direct drive instead of a motor/gear combination, this can often be beneficial from an energy perspective due to the lower friction. However, using a linear direct drive, stepper motors or DC motors can also make sense for energy reasons. No one motor is ideal for all applications. Measurements or simulations can be used to determine the losses in the application, if detailed simulation models are available.

Use of efficient motors	★
Relevance If a choice of different motors is available	**Expense** Comparison of motor losses in the design
Applicability **30%**	**Savings up to** **3%**

5.2.6 Use of efficient servo controllers

In addition to selecting the right size of servo controller, losses in the electronics also play a key role. The servo controllers used should therefore be as efficient as possible. Two selection criteria are important. On the one hand, there are losses dependent on the load, which must be as low as possible. One criterion for this is a higher rate of efficiency, even if this only allows losses to be roughly estimated, unless the system is oversized. The second criterion is the power consumption when the motor is idle or in standby mode. Servo controllers generally also draw power in this state, which can have a significant impact on the overall energy consumption, especially for low drive powers and long idle periods. As with other components, the losses which occur can only be determined with detailed specifications or simulation models.

Use of efficientservo controllers	★★
Relevance If a choice of servo controllers is available	**Expense** Comparison of electronic losses in the design
Applicability **20%**	**Savings up to** **3%**

5.2.7 Minimising the motor cable length

The motors are connected to the servo controller via a multi-core motor cable. The resistance of the cable causes losses, which increase with the length of the cable. Also, the cables, which are generally shielded, adversely affect the switching characteristics of the servo controllers and can cause additional losses in the servo controller. This is particularly relevant for low power drive systems. It can therefore make sense in larger automation systems not to install all servo controllers in one location, but to fit them decentrally near the motors.

Minimising motor cable length ★	
Relevance For low power drive systems with very long motor cables and scope to alter the layout	**Expense** Incorporation in planning
Applicability **5%**	**Savings up to** **2%**

5.2.8 Using the braking energy

Typical positioning processes involve cyclical acceleration and braking. During the acceleration phases, the drive motor is supplied with electric energy, which is then partially converted to the kinetic energy of the moving masses, and partially lost. During the braking phases, this kinetic energy is converted back to electric energy by the drive motor, which also results in losses. Depending on the drive system, part of the recovered braking energy can be stored in capacitors. If their storage capacity is not sufficient, resistors are activated to convert the braking energy into heat. As soon as these resistors are activated, electric energy is lost. When designing a drive system, it is important to determine whether and how much braking energy is present and whether it can be stored in an intermediate circuit.If the storage capacity is not sufficient, it can be expanded via several measures:

1. The intermediate circuit capacity can be increased by connecting additional capacitors in parallel. If the servo controller supports this, this can also be achieved by connecting to a passive additional storage module. These modules only consist of capacitors with passive circuits.

2. If multiple drives are to be operated side-by-side, it is possible to check whether they can be operated with a shared DC voltage intermediate circuit. That can either be done using a multi-axis servo controller or via electrical connection of the intermediate circuits, if this is technically possible. That increases the intermediate circuit capacity, which is only useful if multiple drives do not brake at the same time. The energy can also be used directly, if one drive requires energy for acceleration while another drive is in the braking phase.

3. If these two options cannot be implemented, or the storage capacity is not sufficient, an active additional storage module can be used. For further information, see the “Optimisation approach” below.

In any case, the energy flows must be analysed beforehand, which can be done in calculations and simulations if details of the application are known.

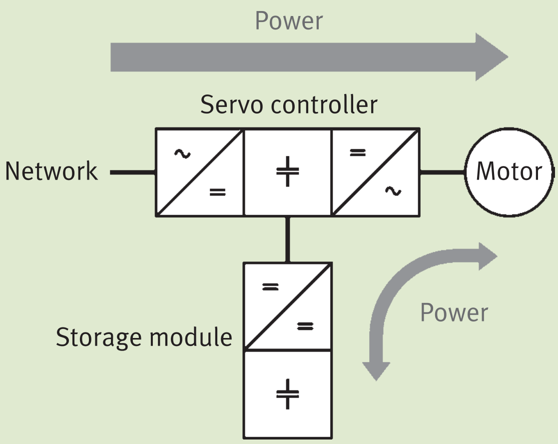
Use of braking energy ★★	
Relevance For highly dynamic drives in which the servo controller’s storage capacity is not sufficient	**Expense** Shared intermediate circuit or addition of a storage module
Applicability **10%**	**Savings up to** **5%**

Optimisation approach

Buffer storage module to buffer braking energy

In general, the intermediate circuit storage capacity of motor controllers is rather small for cost reasons. In applications with extremely dynamic movements, this energy storage often cannot absorb all of the braking energy, which is why it is converted to thermal energy. During the project a variable buffer module was developed, which can be connected to the direct current intermediate circuit of the servo controller, and then can buffer larger amounts of braking energy with few losses.

The buffer module consists of a power electronics circuit and a storage capacitor. The circuit is a bidirectional direct current actuator, which can charge and discharge the storage capacitor dynamically. That allows a far greater amount of energy to be stored in the capacitor than if it were only connected passively to the intermediate circuit. In a braking phase, the braking energy is transferred to the storage capacitor. This stored energy is fed back into the intermediate circuit during subsequent acceleration phases, and reused to accelerate the motor. A disadvantage of this system is that losses are higher than with a passive buffer module. The function was tested with a gantry drive and 17% of the energy was saved compared with standard operation. However, the potential savings depend greatly on the individual application.



Commissioning and optimisation in operation

The following measures can be used when commissioning new systems and to optimise existing systems. They do not require changes to the structure, but they affect the control.

5.2.9 Adapting the movement profile

The choice of the movement profile has a major impact on the energy consumption. The movement profile is the shape of the time curves of acceleration, speed and travel. In practice, there are many movement profiles. If the parameters permit, energy-optimised movement profiles should be used where possible. For example, the time per movement has a major effect on the energy consumption, so the movement should be implemented as rapidly as required by the application.

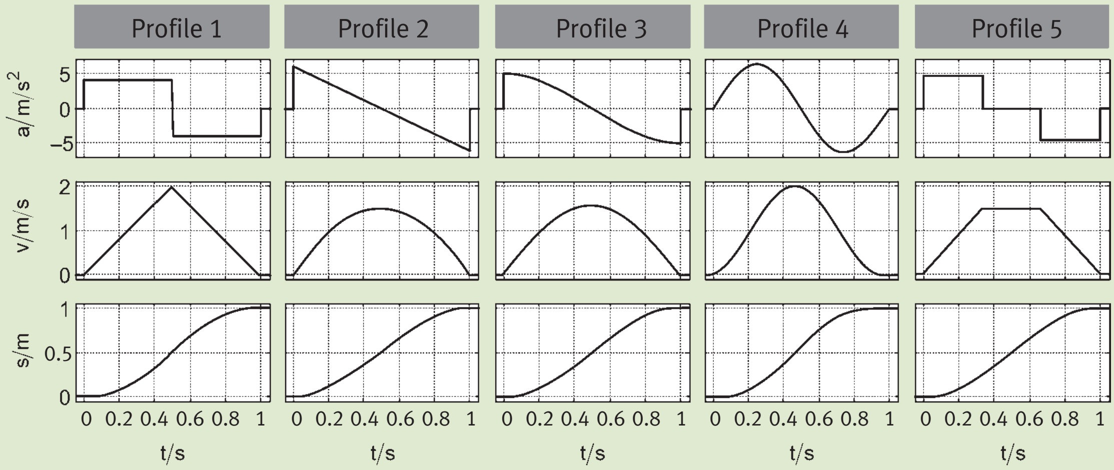
Adapting the movement profile ★★★	
Relevance If the application permits movement tolerance or there is a time buffer	**Expense** Change of the movement specification in the control unit
Applicability 20%	**Savings up to 8%**

Optimisation approach

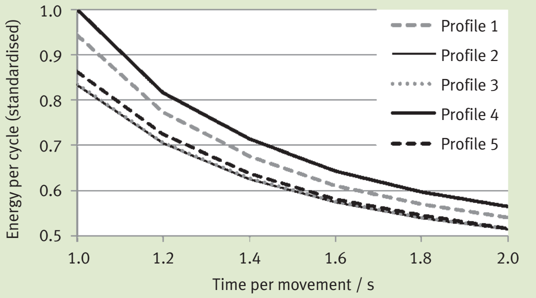
Influence of the movement profile and the time per movement

During the project five movement profiles were compared. They were all selected as the moved object travelled the same distance in the same time. The curve of the path (s) only differs minimally, although the curves for speed (v) and acceleration (a) differ substantially.

Profile 1 is also known as the time-optimal profile, as it minimises the time per motion for a given maximum acceleration. The acceleration phase transitions directly to the braking phase.
Profile 2 is the energy-optimal profile, as it can be derived by minimising the effective value of acceleration, which acts as a measure for the losses in a simple approximation.
Profile 3 is very similar to Profile 2, but has a cosine shaped acceleration curve.
Profile 4 is a jerk-free movement profile and
Profile 5 is a derivative of Profile 1, with a time interval at constant speed.



The following diagram shows the standardised electric energy required by an electric motor per movement cycle. It shows that the energy demand depends largely on the movement profile. With identical parameters, it differs by up to 17%. Energy-optimal profile 2 always requires the least energy, and, due to the great similarity, profile 3 only requires slightly more. In addition to this, the energy demand increases sharply as the time per movement decreases, which corresponds to an increase in speed and acceleration.



5.2.10 Reducing vibrations in the control system

Energy-efficient control is achieved when the transient response is as low vibration as possible. Every vibration results in a compensating process which requires power. If vibrations occur in the application, they should be eliminated with the standard optimisation processes offered by control engineering. Correctly configured controllers do not offer optimisation potential, as optimisation of the guide characteristics already indirectly minimises the energy consumption.

Reducing vibrations in the control system	★★
Relevance For vibrating controlled systems and poorly configured controllers	**Expense** Optimisation of the controller settings or change of the closed-loop control structure
Applicability **10%**	**Savings up to** **10%**

Optimisation approach

Comparison of the energy efficiency of drive systems via simulation

Energy efficiency rating
The electricity consumption at stationary operating points can be calculated using efficiency ratings; this enables the energy efficiency and thus the energy saving potential to be determined. In the area of automation and handling technology, many drives are in non-stationary operation – they accelerate and brake cyclically. Efficiencies largely depend on the respective operating point, and are not known for every point. As a result, they do not allow an objective evaluation of which drive system has the lowest energy consumption for the same application. The energy demand is affected by the interaction of all components and not least by the control unit. For an objective evaluation of energy efficiency, the drive system must be considered as a whole.

Evaluation variable
In order to evaluate the energy efficiency of electric drive systems in non-stationary operation, the electric energy consumption per movement cycle is suggested as a comparison criterion; this is defined as an integral of the overall intake of electric power during a movement cycle.

$$E_{Cycle} = \int_{Cycle} P_{Tot}(t)dt$$

This variable makes an objective evaluation possible, as it contains all losses of the system, such as the mechanical losses, motor losses and losses from the power and signalling electronics. The latter are non-negligible, especially for low power drives (<1 kW) with long movement breaks.

Determination of the evaluation variable via simulation
The comparison variable “energy” is to be available for system design. Measurements with various combinations of components cannot be made within a reasonable time frame during the planning phase. As a result, the required amount of energy should be determined via simulation with a model of the drive system. The energy consumption of the models should be accurate. They should not only include the mechanical components, motors and control unit, but they should also feature electric components such as pulse inverters, direct current intermediate circuit and grid feed-in. The structure of the models should be a compromise between being an exact model and a simple parameterisation. This will facilitate the precise modelling of the system characteristics and losses – without making it too complex to produce the model and enabling the simulation to be implemented quickly and easily.

As part of the EnEffAH project, simulation models were developed to compare the energy efficiency of model drive systems. In order to use the evaluation method in practice, models of all possible drive systems must be available to compare them with one another. It is conceivable that the simulation models would be standardised and that drive manufacturers provide these models or their parameters for comparisons.

6 Overview of measures

6

The following section summarises the measures presented in this paper in two tables for a better overview.

Each of the individual measures presented can be used to unlock potential for energy efficiency. The measures affect one another, so that that implementation must always be evaluated in an overall context. Some individual measures are even mutually exclusive (e.g. general pressure drop and efficient design of drives).

Note on adding the efficiency increases
Mutual influences prevent statements to be made on increases in the overall efficiency of a system on the basis of the values presented here. The percentage efficiency increases cannot simply be added to determine an overall energy saving.

Nor can the percentage savings with the measures presented in pneumatics and electric drive and handling technology be compared directly with one another, as they are based on different parameters.

6.1 Overview of the measures in pneumatic drive and handling technology

	Chap.	Measure	Appli-cability	Savings up to	Evalu-ation
Provision	4.1.1	Compressor design and integrated control unit	20%	20%	★★★
	4.1.2	Central heat recovery	50%	96%*	★★★
	4.1.3	Speed-controlled compressors	25%	15%	★★
	4.1.4	Lowering the system pressure	50%	15%	★★
Preparation	4.2.1	Drying compressed air			
		Refrigeration dryer	60%	2%	★
		Adsorption drying	10%	20%	★★
	4.2.2	Design of the compressed air preparation unit	20%	10%	★★
	4.2.3	Regular maintenance of the compressed air preparation	80%	20%	★★★
Distribution	4.3.1	Optimised sizing of pipes	20%	10%	★★
	4.3.2	Optimising the system infrastructure	40%	5%	★
	4.3.3	Sturdiness and positioning of buffers	40%	10%	★★
	4.3.4	Elimination of leakages in the system	80%	5%	★★★
Application	4.4.1	Correct design of drives and components	80%	40%	★★★
	4.4.2	Avoiding dead volume	30%	20%	★★
	4.4.3	Leakage detection and elimination (system/application)	70%	20%	★★★
	4.4.4.1	Single-acting cylinders	10%	50%	★★
	4.4.4.2	Short-circuit valve	10%	43%	★★
	4.4.4.3	Supply air flow control & deliberate deactivation	30%	50%	★★
		Optimised valve control	30%	65%	★★

* Out of all the measures, central heat recovery occupies a special place. The savings shown here are not actually savings as such. The energy created via heat recovery is an additional benefit which can be utilised in other areas.

The energy savings discussed as part of all the measures refer to the energy consumption of the particular part of the system under investigation. Percentage savings in the table should not be compared with one another as the starting point always differs. For example, pneumatic applications in drive and handling technology only account for a small proportion of the compressed air consumption in a company (assumption: approx. 20%). Relative to the entire compressed air usage of a company, the percentage savings for measures in pneumatic applications are therefore lower than those specified in the table. That is why these specifications are supplemented with a rating (one to three stars), which weigh up the benefits and expenses of the measure.

6.2 Overview of the measures in electric drive and handling technology

	Chap.	Measure	Appli-cability	Savings up to	Evalu-ation
Provision	**5.1.1**	Optimising low voltage direct current supply	10%	2%	★
	5.1.2	Reducing energy consumption in standby mode	20%	5%	★★
Planning	**5.2.1**	Using low-friction mechanical components	10%	20%	★★★
	5.2.2	Minimising moving masses	10%	15%	★★★
	5.2.3	Avoiding oversizing	50%	10%	★★
	5.2.4	Optimising energy consumption in breaks in movement	10%	4%	★★
	5.2.5	Use of efficient motors	30%	3%	★
	5.2.6	Use of efficient servo controllers	20%	3%	★★
	5.2.7	Minimising the motor cable length	5%	2%	★
	5.2.8	Use of braking energy	10%	5%	★★
Drives & application	**5.2.9**	Adapting the movement profile	20%	8%	★★★
	5.2.10	Reducing vibrations in the control system	10%	10%	★★

The measures presented and their energy efficiency potential always refer to the overall energy consumption of the electric drive and handling unit(s). As a result, they cannot be compared directly with the savings for pneumatic measures.

6.3 The path to energy-efficient drive and handling technology

Step 1 – First aid

Low expense - High benefit

Pneumatic drive and handling technology:
The most important, and luckily the simplest energy efficiency boosting measure to implement in virtually all systems is to find and eliminate leakages. This can either be done by the company's own employees or – if there are time constraints or the required expertise and equipment are not available – by an external service provider. Regular maintenance of the components of the compressed air preparation system also results in energy savings at a justifiable cost.

Electric drive and handling technology:
The energy efficiency potential of existing systems can be unlocked without major intervention by optimising the movement profiles of the drives and by reducing vibration in the control unit.

Step 2 – Creating awareness

Requirements to allow energy efficiency to be put into practice and applied permanently

In a second step, employees' awareness of energy efficiency should be raised and barriers must be broken down. This is essential to ensure that the measures implemented are successful in the long term. This newly raised awareness should also be communicated to suppliers (e.g. in performance specifications) and customers (e.g. via marketing).

Step 3 – Become an energy efficiency champion!

Measures with positive benefit/expense ratios

All measures presented in this paper are important steps towards energy-efficient production and can be implemented economically in most companies. However, every company must check individually which measures promise the best benefit/expense ratio and prioritise them accordingly.

- Efficient component design
- Reducing moving masses
- Reducing friction in the system
- Using operating strategies (pneumatics): single-acting cylinders, short-circuit valves, deliberate deactivation of the compressed air supply, etc.
- Avoiding dead volume (pneumatics)
- Efficient compressor control with splitting systems or speed-controlled compressor (pneumatics)
- Heat recovery on compressor (pneumatics – up to 96% of the energy used can also be used as heat)
- Reducing energy consumption in standby mode (electric drives)

7.1 Conclusions

7

This paper is intended as a guideline for users to design energy-efficient handling technology.

It shows that there are numerous approaches to improving energy efficiency. Technical and economical considerations generally prevent all measures presented being implemented, but by selecting the right measures and using drive and handling technology correctly, notable energy and cost savings can be reached in almost every company without performance deteriorations.

The amount which can be saved usually depends on the specific local parameters. The measures themselves also play a role: some of the measures can be implemented with very little expense, while others are better suited as part of a system refurbishment or new system installation. Having a holistic view of energy efficiency, rather than focusing exclusively on individual components, is also important. Continuous consideration of energy efficiency is more effective than a sporadic approach. It is important that energy efficiency is entrenched throughout the organisation if, in addition to energy-efficient technical solutions, a lasting and broad awareness of using energy sensibly at work is to be created.

Please remember that an interdisciplinary technological approach is essential for optimal system design. Electric and pneumatic drive technologies each have specific advantages and disadvantages, both in terms of energy consumption and other aspects, such as flexibility and costs. Optimal application design is generally only possible after a careful analysis and consideration of these aspects. If this cannot be done in-house, technology suppliers can provide assistance. In addition, more and more energy-oriented services are now being offered to support users on-site.

There are many ways to be energy-efficient! Make the most of them!

For more information on the project, visit **www.eneffah.de.**

7.2 Contacts

For expert assistance in all areas covered in this paper, contact any EnEffAH Project Industry and Research Partner.

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7.3 Publications from the project

The following publications were issued as part of the project:

F. Blank, J. Roth-Stielow: **Bewertungsmethode für die Energieeffizienz eines elektrischen Antriebssystems (Method for evaluating the energy efficiency of an electric drive system)**, Tagungsband zur SPS/IPC/Drives 2010 (23. - 25.11.2010, Nürnberg), pp. 321-329.

F. Blank, J. Roth-Stielow: **Energieexakte Simulationsmodelle zur Bewertung der Energieeffizienz (Precise energy simulation models for evaluating energy efficiency)**, Tagungsband zum Internationaler ETG-Kongress 2011 (08.-09.11.2011, Würzburg).

F. Blank, J. Roth-Stielow: **Vergleich der Energieeffizienz von Antriebssystemen durch Simulation (Comparing energy efficiency of drive systems by simulation)**, Tagungsband zur SPS/IPC/Drives 2011 (22. - 24.11.2011, Nürnberg), pp. 481-489.

M. Doll, O. Sawodny: **Energy Optimal Open Loop Control of Standard Pneumatic Cylinders, Proceedings of the 7th International Fluid Power Conference (IFK)**, Aachen, April 2010, pp. 259-270.

M. Doll, O. Sawodny: **Modellbasierte, adaptive Steuerung für energieoptimale Bewegungsvorgänge in schalt-pneumatischen Antrieben (Model-based adaptive control for energy-optimal movements in switching pneumatic drives)**, In: Tagungsband des GMA-Fachausschuss 1.30 – Modellbildung, Identifikation und Simulation in der Automatisierungstechnik, Salzburg, 21.-23.09.2011, pp. 9-22

M. Doll, R. Neumann, O. Sawodny: **Energy efficient adaptive control of pneumatic drives with switching valves**, submitted for oral presentation at IFK 2012, Dresden, 2012

M. Doll, R. Neumann, O. Sawodny: **Energy efficient use of compressed air in pneumatic drive systems for motion tasks**, International Conference on Fluid Power and Mechatronics (FPM), Beijing, August 17-20, 2011, pp. 340-345.

S. Hirzel, R. Elsland, M. Schroeter, U. Weissfloch: **Energy efficiency improvements in compressed air systems: A techno-economic evaluation approach**, Proceedings of the ICMC 2010 - Sustainable Production for Resource Efficiency and Ecomobility (29. / 30. September 2010, Chemnitz), pp. 695-703.

J. Kefer, S. V. Krichel, O. Sawodny: **Modeling and simulation of pneumatic systems with focus on tubes**, submitted for oral presentation at IFK 2012, Dresden, 2012.

S. V. Krichel, O. Sawodny: **Modellierung von Druckluft-leitungen - Ansätze und Ergebnisse (Modelling compressed air lines - approaches and results)**. In: Tagungsband GMA-Fachausschuss 1.30 - Modellbildung, Identifikation und Simulation in der Automatisierungstechnik, Anif/Österreich, 22.-24.09.2010. 2010, pp. 184-194.

S. V. Krichel, O. Sawodny: **Modelling and Optimization in Pressurized-Air Networks – A first Approach with Respect to Energy-Efficiency**, Proceedings of the 7th International Fluid Power Conference (IFK), Aachen, April 2010, pp. 317-328.

S. V. Krichel, O. Sawodny: **Analysis and optimization of compressed air networks with model-based approaches**, Ventil 17(2011)4, 2011, pp. 334-341

S. V. Krichel, O. Sawodny: **Dynamic modeling of compressors illustrated by an oil-flooded twin helical screw compressor**, Mechatronics, 2011, 21, pp. 77 - 84.

S. V. Krichel and O. Sawodny, **Dynamic Modeling of Pneumatic Transmission Lines in Matlab/Simulink**, Proceedings of the International Fluid Power and Mechatronics Conference, Beijing/China, August 17-20th, 2011, pp. 24-29 (Best conference paper finalist).

S. V. Krichel, O. Sawodny: **Model-based analysis of pneumatic networks - prospects and challenges**, Proceedings of the Twelth Scandinavian International Conference on Fluid Power (SICFP'11), Tampere (Finland), May 18-20th, 2011, pp. 471-483.

S. V. Krichel, O. Sawodny: **Non-linear friction modeling and simulation of long pneumatic transmission lines**, submitted to IFAC Mechatronics (under review), 2011.

S. Krichel, S. Hülsmann, S. Hirzel, R. Elsland, O. Sawodny: **Mehr Klarheit bei der Druckluft: Exergieflussdiagramme als neue Grundlage für Effizienzbetrachtungen bei Druckluftan-lagen (Greater clarity in compressed air: exergy flow diagrams as a new basis for efficiency studies of compressed air systems)**, O+P, Nr. 01-02, 2012.

S. V. Krichel, S. Hülsmann, S. Hirzel, O. Sawodny, R. Elsland: **Exergy flow diagrams as a novel approach to discuss the efficiency of compressed air systems, submitted for oral presentation at IFK 2012**, Dresden, 2012.

Q.-K. Nguyen, J. Roth-Stielow: **Rückgewinnung der Brems-energie bei Antrieben in der Automatisierungs- und Hand-habungstechnik (Recovering braking energy in drives for automation and handling technology)**, Tagungsband zur SPS/IPC/Drives 2011 (22. - 24.11.2011, Nürnberg), pp. 511-519.

U. Weissfloch, K. Mattes, M. Schroeter: **Identifizierung aussichts-reicher Geschäftsmodelle für die Druckluftversorgung (Identifying promising business models for compressed air supply)**, Presentation at GOR Workshop Vector Optimization of Complex Structures, (17. – 19.03.2010).

U. Weissfloch, K. Mattes, M. Schroeter: **Multi-criteria evaluation of service-based new business concepts to increase energy efficiency in compressed air systems**, i-SUP 2010, Innovation for sustainable production, Conference 1. Sustainable Production, Proceedings, pp. 61-65.

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