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Electric or pneumatic? Comparing electric and pneumatic linear drives with regard to energy efficiency and costs

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Abstract

Linear drives are broadly used in industrial automation, e.g. for material handling systems, assembly lines or machine tools. In many applications, both compressed-air powered pneumatic drives as well as linear electric drives can be used. The use of compressed air is generally associated with comparatively low energy efficiency. This has triggered a debate about the energy-related performance of alternative drive systems.

In this paper, we contribute to this debate by providing insights into the energy efficiency and costs of pneumatic and electric linear drives. For this purpose, we introduce and apply a simple framework for comparing these two types of drives. Within this framework, we systematically analyze the impact of varying framework conditions on the comparison and we show how variations of these conditions affect the results.

Our findings underline that electric linear drives tend to be more energy-efficient and less expensive under certain conditions while in other cases, the opposite is true. Thus, general statements about the energy efficiency and costs of pneumatic and electric linear drives can be misleading. While our results allow identifying general trends, a case-based in-depth analysis is advisable to determine which linear drive technology is most suitable for a specific application.

Introduction

Considerations on the appropriate use of compressed air have a long tradition (e.g. Saunders 1892). Today, roughly 10 % of the industrial electricity demand in Europe is used for generating compressed air (e.g. Radgen et al. 2001). This corresponds to an annual electricity demand of approximately 100 TWh (Eurostat 2013). Compressed air is needed for a large variety of different purposes, e.g. in process engineering, for material transport, for vacuum generation, for testing and as working air to drive compressed air tools and pneumatic drives (Figure 1). As a subgroup of compressed air end-uses, pneumatic drives serve to generate linear and rotatory movements that are required for many tasks in industrial automation such as material handling systems, assembly lines or machine tools. In total, pneumatic drives account for roughly 30 % of industrial compressed air demand (Krichel et al. 2012). This translates into an annual electricity demand of some 20 to 30 TWh for Europe.

In general, the typical useful energy output associated with the use of compressed air applications is relatively low and estimated at about 10 % (e.g. Müller et al. 2009; Galitsky et al. 2008; Albrecht 1993; Münst 1992). This has triggered a debate whether it is best to substitute compressed air end-uses by alternative technologies, i.e. especially electrically driven alternatives (e.g. Pohl et al. 2011; Berchten et al. 2006; SEA 2003; Albrecht 1993; Münst 1992). While it has been pointed out that depending on their intensity of use, pneumatic drives may be more energy-efficient than electric ones (Cai et al. 2002), there is currently no broader analysis of this topic.

As a contribution to the debate, we therefore aim to provide a broader view of the comparison of electric and pneumatic linear drives. For this purpose, we suggest a simple framework for a structured investigation on the energy efficiency and costs

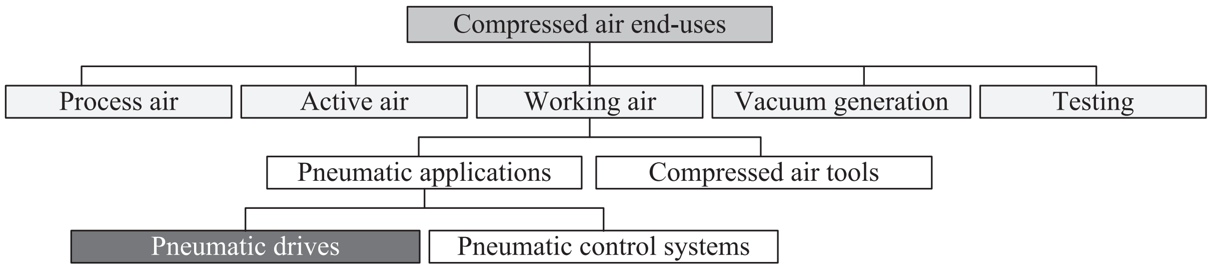

Figure 1. Overview of compressed air end-uses.

of pneumatic and electric linear drives. This framework is to allow comparing both types of drives and analyzing how changes in framework conditions (such as operating and stand-by time, leakages or heat recovery, altered lifetimes or investments) generally affect the results of such a comparison.

For this purpose, we proceed as follows: We start by outlining conditions for a comparison of electric and pneumatic drives. This is followed by the introduction of a framework for comparing both drive technologies with regard to their energy efficiency and costs. We then apply this framework to a set of double-acting linear pneumatic drives and electric spindle-type drives. Within this analysis, we investigate the impact of varying framework conditions on the comparison. Finally, we discuss observations from our analysis and uncertainties related to our method and results.

Methodology

CONDITIONS FOR COMPARING PNEUMATIC AND ELECTRIC LINEAR DRIVES

Comparing pneumatic and electric linear drives requires that some preliminary conditions are fulfilled. The first precondition is that both drive technologies achieve a similar technological performance. That means that they handle similar maximum loads within identical cycle times and that they have comparable acceleration and velocity profiles. Using these performance parameters instead of simply comparing the drives by their size is necessary as the power density of pneumatic drives tends to be higher than the power density of electric drives (e.g. Watter 2008; Albrecht 1993). A second precondition concerns specific environmental requirements of the applications. A comparison of electric and pneumatic linear drives is only valid if both drives actually meet application-specific requirements such as robustness (e.g. cement industry), explosion protection (e.g. hazardous environments) or hygienic standards (e.g. food industry).

Only if these conditions are fulfilled, it makes sense to compare electric and pneumatic linear drives. In that case, several additional remarks have to be taken into account. First, both technologies include many different types of drives. Pneumatic linear drives typically consist of a cylinder, a valve linked to a control system, piping for conducting air between the valve and the cylinder and additional equipment (e.g. maintenance units, sensors and other small parts). Pneumatic cylinders include cylinders with no, one or two rods, single-acting and double-acting cylinders and so on. Similarly, there are various types of electric linear drives including direct drives, belt or chain drives or spindle-type drives. The latter consist of an electric motor and a mechanical axis in addition to other small parts. The energy demand of a specific application will not only depend on the actual technological parameters of operation and the framework conditions, but also on the selected type of drive. For example, the use of single-acting cylinders instead of double-acting cylinders may help to cut the compressed air demand by approximately half, as no air is required for the return stroke of the cylinder. However, this may come at the detriment of the dynamic performance of the drive. Therefore, generalizing comparisons of linear drives are always simplifications that have to be checked for their validity in specific situations.

Secondly, there are differences in the structure of the upstream energy supply systems for pneumatic and electric linear drives. Pneumatic drives are usually part of large compressed air systems. These systems consist of one or several centrally located air compressors, a set of filters, dryers and separators for air treatment, a distribution network and a multitude of different end-uses including the pneumatic drives. While pneumatic drives require the conversion of electric power into compressed air, electric drives operate directly on electric energy. This energy is usually provided by a decentralized control system which often includes a low-voltage power supply. When comparing both types of drives, equal system boundaries have to be chosen. These boundaries encompass the entire supply side of a compressed air system in the case of pneumatic drives. In the case of electric linear drives, this corresponds to boundaries that encompass the electric power supply including the control system of the drive (Figure 2). If the components of the supply side serve more than one drive or other end-use, it is important to note that there is an allocation problem. This means that there is no objective way of associating energy demand or costs of the supply system to individual applications of the demand side, i.e. end-uses.

Thirdly, comparing the costs of pneumatic and electric drives means that all costs that are relevant for a decision-maker have to be taken into consideration. Determining the relevant costs is not always an easy task. If a pneumatic drive can be powered by an existing compressed air system, for example, only the additional costs for the drive are relevant for decision-making. On the other hand, if an additional compressor is needed for operating the drive, the costs of the compressor are relevant for the decision-maker as well. Thus, depending on the situation, relevant costs may vary. Furthermore, if the pneumatic and electric linear drives and their additional components do not have the same lifetime, investments for replacements and end-values have to be included in the comparison. And finally, it is also important to note that the selection of the scope in terms

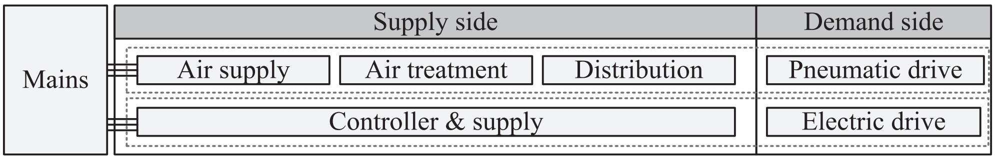

Figure 2. Structure of the energy systems and system boundaries for a comparison.

of time is important for the results, as a longer scope means that differences in operating costs gain in importance as compared to initial investments.

APPROACH FOR THE COMPARISON OF ENERGY EFFICIENCY

Taking these conditions and remarks into consideration, we now proceed to the introduction of a simple framework for comparing electric and pneumatic drives. For the analysis, we assume that comparability is given, i.e. that pneumatic and electric drives show a similar technological performance and that there are no special environmental requirements that impede the use of either technology.

If equal system boundaries are selected and if the same scope is used, we can state that electric and pneumatic drives perform equally well with regard to energy efficiency if the energy demand of the pneumatic drive E_{pn} equals the energy demand of the electric drive E_{el}, thus:

$$E_{pn} = E_{el} \tag{1}$$

Note that we only focus on energy demand and implicitly assume that the energy service provided by both types of drives is equal. In that case, it is obvious that if energy demand for one drive technology is lower, this drive is superior with regard to energy efficiency.

For our further analysis of energy demand, we assume a scope that covers a single operating cycle with the duration t_{cyc}. This cycle consists of three states: First a back-and-forth motion. Within this part of the cycle the drives start from an initial position, they execute a single outward stroke and then return back to their initial position. Second a holding state where the drives may exert forces to hold an object for some time. Third, a period of stand-by, i.e. the drives are idle for the rest of the cycle. For the sake of simplicity we assume that there is no overlap of these three different states. Then we can restate our initial equation by:

$$E_{pn,m} + E_{pn,h} + E_{pn,s} = E_{el,m} + E_{el,h} + E_{el,s} \tag{2}$$

with $E_{pn,m}$ and $E_{el,m}$ as the energy demand for the back-and-forth motion of the pneumatic respectively the electric drive, $E_{pn,h}$ and $E_{el,h}$ as the respective energy demand for the holding functions of the drives and $E_{pn,s}$ and $E_{el,s}$ as their energy demand during stand-by. The duration of one complete cycle t_{cyc} equals the sum of the duration for moving t_m, holding t_h and stand-by t_s.

In general, the energy demand of a compressed air end-use can be determined by its overall air demand V and by a specific amount of energy required to provide this amount of compressed air e_{pn}. With regard to the stand-by, pneumatic linear drives usually do not have any stand-by demands. However, there might be leakages in the upstream compressed air system that can be considered as stand-by losses. They occur permanently during the entire cycle. Despite the general allocation problem, we treat leakages as if they could be attributed to single pneumatic drives because we will consider stand-by losses in the electric supply system later on. The associated energy losses during stand-by $E_{pn,s}$ can thus be calculated by:

$$E_{pn,s} = v_{pn,loss} \cdot t_s \cdot e_{pn} \tag{3}$$

with $v_{pn,loss}$ as the specific air losses during stand-by.

Similarly, assuming that the pneumatic drive has a specific demand v_h for holding an object, the overall energy demand for holding $E_{pn,h}$ is:

$$E_{pn,h} = \left[v_{pn,h} + v_{pn,loss} \right] \cdot t_h \cdot e_{pn} \tag{4}$$

Finally, we have to determine the energy demand for the back- and forth motion. The compressed air demand required for this motion is determined by the air volume needed by the cylinder $V_{pn,m,cyl}$ and by the piping between the valve and the cylinder $V_{pn,m,pipe}$. The demand of the cylinder depends on the type of cylinder that is used. For a double-acting linear cylinder, its demand $V_{pn,m,cyl}$ can be approximated by:

$$V_{pn,m,cyl} = \pi \cdot \left[\frac{d_{cyl}}{2} \right]^2 \cdot \left(1 - \left[\frac{d_{rod}}{2} \right]^2 \right) \cdot l_{cyl} \cdot \frac{p_{op}}{p_{amb}} \cdot \frac{T_{norm}}{T_{amb}} \tag{5}$$

with d_{cyl} as the diameter of the cylinder, d_{rod} as the diameter of the cylinder rod and l_{cyl} as the length of the stroke. Moreover, P_{op} and P_{amb} are the operating and ambient pressures in absolute terms and T_{norm} and T_{amb} are the norm temperature and ambient temperature. The demand of the piping $V_{pn,m,pipe}$ for this cylinder is roughly:

$$V_{pn,m,pipe} = 2 \cdot \pi \cdot \left[\frac{d_{pipe}}{2} \right]^2 \cdot l_{pipe} \cdot \frac{p_{op} - p_{amb}}{p_{amb}} \cdot \frac{T_{norm}}{T_{amb}} \tag{6}$$

with d_{pipe} as the diameter of the pipe and l_{pipe} as its simple length.

Considering both values as well as stand-by losses from leakages, we can calculate the energy demand during the motion $E_{pn,m}$ by:

$$E_{pn,m} = \left[V_{pn,m,cyl} + V_{pn,m,pipe} + v_{pn,loss} \cdot t_m \right] \cdot e_{pn} \tag{7}$$

After this determination of energy demand for pneumatic drives, we now address electric drives. With regard to their energy demand, we assume that the supply has a fixed power demand $P_{el,loss}$ when in stand-by. If the supply has the efficiency η_{el}, then the energy demand $E_{el,s}$ during stand-by is:

$$E_{el,s} = \frac{p_{el,loss} \cdot t_s}{\eta_{el}} \tag{8}$$

The holding demand $E_{el,h}$ during the cycle of the electric drive with the specific holding demand $P_{el,h}$ can be expressed by:

$$E_{el,h} = \frac{p_{el,h} \cdot t_h}{\eta_{el}} \quad (9)$$

Note that we considered stand-by losses for the pneumatic drives explicitly for every state in the cycle. For the electric drives, however, we assume that the stand-by losses are implicitly included in the specific holding and moving demand.

Finally, the energy demand for a back-and-forth stroke has to be determined. While for pneumatic drives, the energy demand for a back-and-forth stroke can easily be derived by considering volumes, estimations for electric drives need more sophisticated models. In principle, however, we can use the same approach to express the overall demand for the back-and-forth stroke. Based on the energy demand of the entire stroke $E_{el,m,cyl}$, the overall energy demand for moving $E_{el,m}$ is:

$$E_{el,m} = \frac{E_{el,m,cyl}}{\eta_{el}} \quad (10)$$

Based on these outlined equations summarized in Table 1, it is possible to calculate and compare the energy demand for pneumatic and electric linear drives.

APPROACH FOR THE COMPARISON OF COSTS

After introducing the approach to analyze energy demand, we now extend our perspective to an economic evaluation. For this purpose, we chose a simple comparison of costs based on a static approach. For this evaluation, we assume that both drive technologies have an identical lifetime of T years. Moreover, we assume that only the initial investments in the drives and their periphery as well as subsequent operating costs are relevant.

Similarly as before, we can state in general that electric and pneumatic drives perform equally well if their overall costs C are equal:

$$C_{pn} = C_{el} \quad (11)$$

Again the drive with the lower costs performs better than the other one. By splitting up the costs into investments I and annual operating costs c, we can restate the equation by:

$$I_{pn} + c_{pn} \cdot T = I_{el} + c_{el} \cdot T \quad (12)$$

The investments cover all expenditures related to the drive including small parts. To calculate the investments, we take the cylinder or respectively the mechanical axis as a proxy and estimate the overall investments for all other parts of the drive by an add-on factor. For pneumatic drives this leads to:

$$I_{pn} = I_{pn,cyl} \cdot \left(1 + \beta_{pn}\right) \quad (13)$$

with $I_{pn,cyl}$ as the price of the cylinder and β_{pn} as an add-on factor for its periphery. The investments for the electric cylinder are calculated correspondingly.

For the calculation of annual operating costs for electric drives, we focus on costs related to energy demand. For the electric drives, we use the energy demand for one cycle as calculated above, we scale it to an annual operation time t_{year} and we then multiply it by a fixed energy price p. This leads to:

$$c_{el} = E_{el} \cdot \frac{t_{year}}{t_{cyc}} \cdot p_{el} \quad (14)$$

Note that until now, we have not yet taken any investments/costs for the upstream compressed air system into account. For the electric drives, we can assume that the supply system usually powers only a single drive. This supply system is already covered by the add-on to the investments for the mechanical axis. Thus, it does not have to be considered any more. For the compressed air systems, such a one-to-one relation is very unlikely as a single compressed air supply usually serves many end-uses. Attributing costs of compressed air systems to individual end-uses is again subject to the assignment problem. Yet we slightly modify our calculation of costs for the pneumatic drives for a "fair" comparison of the drives and include these costs. For this purpose, we introduce a compressed air price e_{pn} which covers the electricity price as well as a mark-up for the costs of the upstream compressed air equipment. Thus, the operating costs for pneumatic drives are calculated by:

$$c_{pn} = \frac{E_{pn}}{e_{pn}} \cdot \frac{t_{year}}{t_{cyc}} \cdot p_{pn} \quad (15)$$

This approach allows us to compare electric and pneumatic drives with regard to their costs. In combination with the calculation of energy demand, we have a framework to compare electric and pneumatic linear drives with regard to energy efficiency and costs.

REPRESENTATION OF RESULTS

The starting point of our framework was the equality of energy demand and costs. As is evident from our framework, the equality of the drives depends on different parameters. Depending

Table 1. Summary of the calculation of energy demand for a single cycle.

State	Pneumatic linear drive	Electric linear drive
Moving	$E_{pn,m} = \left[V_{pn,m,cyl} + V_{pn,m,pipe} + v_{pn,loss} \cdot t_m\right] \cdot e_{pn}$	$E_{el,m} = \frac{E_{el,m,cyl}}{\eta_{el}}$
Holding	$E_{pn,h} = \left[v_{pn,h} + v_{pn,loss}\right] \cdot t_h \cdot e_{pn}$	$E_{el,h} = \frac{p_{el,h} \cdot t_h}{\eta_{el}}$
Stand-by	$E_{pn,s} = v_{pn,loss} \cdot t_s \cdot e_{pn}$	$E_{el,s} = \frac{p_{el,loss} \cdot t_s}{\eta_{el}}$

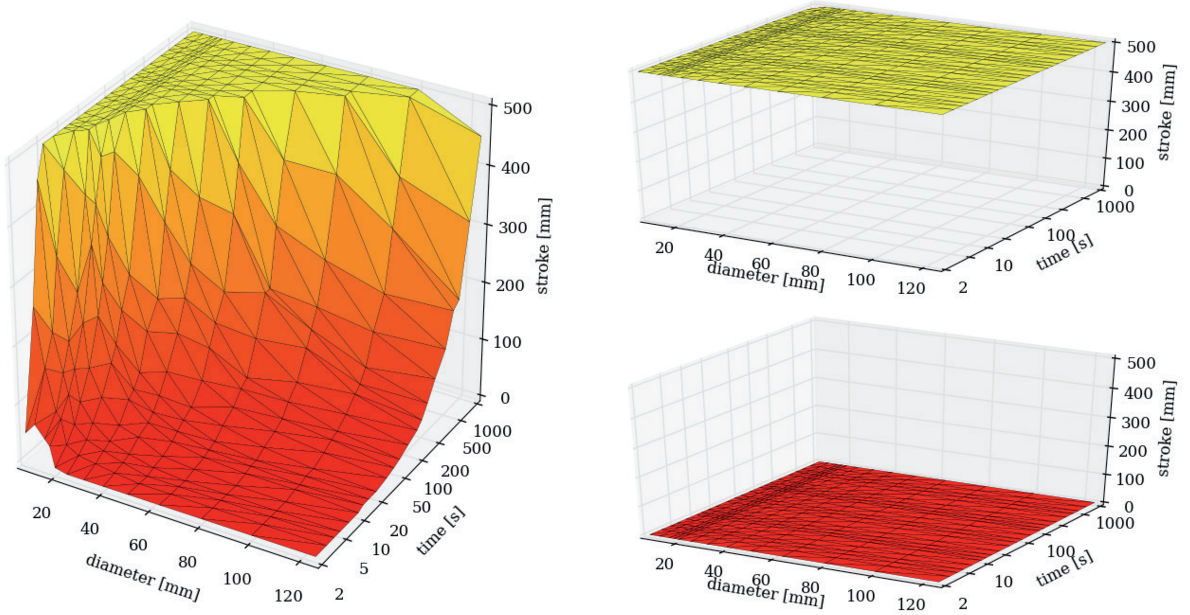

Figure 3. Illustration of concept.

on their values, the points of equality create a plane in a multi-dimensional space. In our case, we choose a three-dimensional representation to visualize this plane. Consequently, we can analyze three different parameters at a time. Important parameters for the analysis of pneumatic linear drives are their diameter, their length of stroke and their cycle time. We therefore use these parameters for the visualization and keep the other parameters constant (Figure 3, left). The resulting plane splits the three-dimensional space into two separate subspaces. The subspace below the plane represents all configurations of diameter, cycle time and stroke where pneumatic drives have energetic advantages (or respectively economic advantages); the other space above the plane represents all configurations where electric drives show a better performance. For instance, a pneumatic drive with the diameter 50 mm, a cycle time of 500 s and a stroke of 100 mm will have a lower energy demand than a corresponding electric drive according to Figure 3 (left). A pneumatic drive with a diameter of 80 mm, a cycle time of 5 seconds and the same stroke will on the contrary have a higher energy demand. Note that the plane continues beyond a stroke of 500 mm but has been truncated for reasons of clarity and data availability. Note further that the colours are only used to improve visual clarity of the representation. Figure 3 (right) shows two extreme cases for illustration. In the upper case, all pneumatic drives with a stroke below 500 mm will perform better than electric drives. In the lower case, electric linear drives outperform pneumatic linear drives for all combinations of diameter, time and stroke.

In the following, we will use this illustration to further analyse electric and pneumatic drives with regard to their energy demand and their costs.

Outline of the analysis

For the application of our framework, we define a baseline as a starting point for our analysis. From this baseline, we will then define a number of different cases where we analyze the impact of modified framework parameters on the comparison of energy demand and costs of electric and pneumatic linear drives.

BASELINE FOR THE ENERGY COMPARISON

As pointed out earlier, there are many different types of linear drives for both technologies. For our analysis, we choose double-acting pneumatic cylinders as proxies for pneumatic linear drives and spindle-type electric cylinders as proxies for corresponding electric linear drives. We first define a set of baseline parameters that do not depend on the diameter, cycle time and stroke of the cylinders (Table 2). While the energy demand for providing compressed air can vary considerably, we chose a value of 0.12 kWh/m³ as a compromise between average compressors (about 0.16 kWh/m³ according to Hesselbach 2012) and good compressors (about 0.10 kWh/m³ according to SEA 2003; Gloor 2000). For the baseline, we further assume that there are no leakages, that we have no holding time, that there is no holding demand for the pneumatic drives and that the average simple length of the piping is 1 meter. For the electric energy supply, we select an efficiency of 80 % as an average value for a low-voltage switched-mode power supply (typically between 70 to 95 % according to EnEffAH 2012) and an average stand-by of 25 Watt. And finally, we define the pressure and temperature levels for our analysis.

In addition to these general parameters, there are others that depend on the three dimensions of our visualisation, i.e. the diameter, stroke and cycle time of the drives. Additional information about the diameter of the rod and the piping is provided in Table 3 for pneumatic drives with different cylinder diameters. Using these parameters in conjunction with our baseline parameters and the equations outlined in our framework, we are able to derive information about energy demand for pneumatic linear drives.

While this calculation is simple for pneumatic cylinders, the determination of electric linear drives with corresponding technological performance requires more complex investigations and detailed technological models. For our analysis, we therefore chose to limit the analysis to 16 representative stroke-diameter combination outlined in Table 4 and to estimate the remaining values using linear inter- and extrapolation.

For the determination of electric linear drives with a similar performance as pneumatic drives, we could rely on modelling results from a joint research project. Within this project, maximum loads for horizontal and vertical movements of pneumatic drives were calculated. Depending on the direction of movement and the size of the drive, the resulting maximum loads vary roughly between 10 and 700 kg. Velocity and acceleration profiles were generated from these loads for each configuration using a dynamic in-detail simulation model for pneumatic drives. These profiles were then used to determine electric spindle-type drives with similar velocity and acceleration profiles for the same loads. For these drives and loads, the energy demands for moving the loads and power requirements during holding were derived. The summary of these results is included in Table 4. Using these parameters in conjunction with previous data, we can calculate energy demand for electric drives and relate them to pneumatic drives with corresponding cylinder diameters.

Table 2. Baseline parameters for the energy comparison.

Parameter	Variable	Unit	Value
Specific demand of air supply	e_{pn}	[kWh/m³]	0.120
Compressed air leakage	$v_{pn,loss}$	[m³/s]	0
Pneumatic holding demand	$v_{pn,h}$	[m³/s]	0
Holding time	t_h	[s]	0
Length of piping	l_{pipe}	[m]	1
Efficiency of electric supply	η_{el}	[%]	80
Stand-by of electric supply	$p_{el,loss}$	[W]	25
Ambient pressure	p_{amb}	[bar$_a$]	1
Operating pressure	p_{op}	[bar$_a$]	7
Ambient temperature	T_{amb}	[K]	293.15
Norm temperature	T_{norm}	[K]	273.15

BASELINE FOR THE COST COMPARISON

In addition to the technical parameters, further input is needed for the comparison of costs. Collecting information on costs is subject to considerable uncertainty as there is a broad range of different drives and prices. Again, we were able to obtain information about some combinations. Table 5 summarizes this set of input data for the comparison. Again, we use linear inter- and extrapolation to calculate values for other sizes. The investments shown in the table include only the cylinder or the mechanical axes. The add-on factor β_{pn} for the pneumatic drives includes investments for additional components such as valves, pneumatic maintenance units, sensors, pipes and other small parts. The add-on factor β_{el} for the electric drives includes the motor, the controller and small parts. While the axes of the electric cylinder are more expensive than pneumatic cylinders, the relative add-on factors have approximately the same size for both drives.

As for the energy comparison, additional parameters and assumptions are required (Table 6). For electricity costs, we assume an average of €0.1/kWh. In conjunction with the specific demand for energy supply, this translates into average specific energy costs of €0.012/m³ for the compressed air. A typical share of the energy costs in the life cycle of the compressed air supply is roughly 70 to 90 % (Saidur et al. 2010). Assuming 80 % as an average, the specific costs for providing compressed air can thus be estimated at €0.015/m³ including electricity. Furthermore, we use an annual operating time of 4,000 hours for the baseline (250 working days in two-shift operation with 8 hours per shift) and a scope of 5 years.

OUTLINE OF CASES

After defining our baseline, we proceed with defining several cases and modify the input parameters for the comparison of energy demand and costs in several ways (Table 7). The first case is our baseline (case 0). Holding operations are considered to improve the energy performance of pneumatic drives

Table 3. Additional baseline parameters for pneumatic drives (source: EnEffAH project).

Parameter	Variable	Unit	Values												
Cylinder diameter	d_{cyl}	[mm]	8	12	16	18	20	25	32	40	50	63	80	100	125
Rod diameter	d_{rod}	[mm]	3	6	6	8	8	10	12	16	20	20	25	25	32
Pipe diameter	d_{pipe}	[mm]	2.6	2.6	2.6	2.6	4.0	4.0	4.0	4.0	5.7	5.7	7.0	7.0	8.0

Table 4. Additional baseline parameters for electric drives (source: EnEffAH project).

Parameter	Variable	Unit	Values															
Stroke	l_{cyl}	[mm]	10	10	10	10	50	50	50	50	100	100	100	100	200	200	200	200
Equivalent diameter	d_{cyl}	[mm]	16	32	63	100	16	32	63	100	16	32	63	100	16	32	63	100
Duration moving	t_m	[s]	0.5	0.5	0.5	0.5	0.8	0.8	0.8	0.8	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.6
Moving demand	$E_{el,m,cyl}$	[Ws]	16	33	53	95	25	55	88	146	40	109	189	316	143	282	461	649
Holding demand	$p_{el,h}$	[W]	31	146	158	600	31	146	158	600	31	146	158	600	31	146	158	600

Table 5. Baseline parameters for the investments of the drives (source: EnEffAH project).

Parameter	Variable	Unit	Values			
Cylinder diameter	d_{cyl}	[mm]	16	32	63	100
Price of the cylinder	$I_{pn,cyl}$	[Euro]	60	90	140	240
Add-on for pneumatic periphery	β_{pn}	[%]	2.5	2.5	2.5	2.5
Price of the mechanical axis	$I_{el,cyl}$	[Euro]	400*	500	700	1200*
Add-on for electric periphery	β_{el}	[mm]	2.5*	2.5	2.5	2.5*

* own estimations

as compared to electric ones. We therefore analyse the impact of increasing the holding time to a 20 % share of the overall cycle time (case 1). The next case concerns the effect of the piping of pneumatic cylinders. For the analysis, we increase the length from 1 to 5 meters (case 2). Then we have a closer look at leakages due to their important effect on the energy demand of compressed air systems (Agricola et al. 2005). For this purpose, we associate a small leakage with a diameter of 0.1 millimetres to the pneumatic drive (case 3) and in addition, we analyse the impact of a larger leakage with a diameter of 0.5 millimetres (case 4). The corresponding specific air losses for these leakages are calculated using BFE (2013). Correspondingly to the analysis of leakages, we reduce the stand-by demand of the electric drives to 5 Watt (case 5). Furthermore, we analyse the effect of heat recovery systems on the performance of pneumatic drives as they can sometimes considerably increase the energy efficiency of compressed air systems by saving energy in heating systems (European Commission 2008). For our analysis, we assume that roughly 70 % of the energy input used to generate air can be recovered to reduce the energy demand of a gas boiler with an average gas price of one third of the electricity price. As heat recovery usually requires additional investments, we increase the mark-up for investments included in the compressed air price by 5 % at the same time (case 6). Note also that heat recovery leads to savings in heating systems and not in compressed air systems. Therefore, heat recovery is sometimes treated separately from other energy efficiency measures (McKane et al. 2010).

In addition to these six cases affecting both energy demand and costs, we analyse some cases where we only change parameters which affect the comparison of costs. For this purpose, we reduce the annual operating time to single-shift operation (case 7). Furthermore we change our assumptions on the lifetime of the drives from 5 to 7 years (case 8). And finally, as a precise determination of investments for the electric drives is subject to considerably uncertainties, we reduce the investments for the mechanical axes. For this purpose we assume that the electric linear drives and thus the additional components (and consequently their periphery) are only two times more expensive than the pneumatic linear drives (case 9).

Results

Using the described data, we proceed to a comparison of energy demand and costs. Due to numerous factors that influence the comparison, we first analyze the baseline and conduct a brief sensitivity analysis. We then continue with the different cases.

Table 6. Additional parameters for the comparison of costs.

Parameter	Variable	Unit	Value
Electricity price	p_{el}	[€/kWh]	0.1
Costs of compressed air	p_{pn}	[€/m³]	0.015
Annual operating time	t_{year}	[h]	4000
Scope	T	[a]	5

Table 7. Overview of modified baseline parameters.

Case	Description	Unit	Modified parameter
0	Baseline	–	–
1	20 % of the cycle time are used for holding operations	[s]	$\hat{t}_h = 0.2 \cdot t_{cyc}$
2	Length of piping extended to 5 meters	[m]	$\hat{l}_{pipe} = 5$
3	Assumed leakage of 0.1 mm	[l/s]	$\hat{v}_{pn,loss} = 0.0086$
4	Assumed leakage of 0.5 mm	[l/s]	$\hat{v}_{pn,loss} = 0.2152$
5	Reduction of electric stand-by to 5 Watt	[W]	$\hat{p}_{el,loss} = 5$
6	Use of a heat recovery at the compressor	[kWh/m³]; [€/m³]	$\hat{e}_{pn} = 0.036$; $\hat{p}_{pn} = 0.01235$
7	Single-shift instead of double-shift operation	[h]	$\hat{t}_{year} = 2000$
8	Scope extended to 7 years	[a]	$\hat{T} = 7$
9	Reduction of investments for electric drives	[€]	$\hat{I}_{el,cyl} = 2 \cdot I_{pn,cyl}$

RESULTS FOR ENERGY DEMAND

Figure 4 (left) shows the results of the energy analysis for the baseline (case 0). The visual representation clearly indicates that there are combinations of stroke, diameter and cycle time where pneumatic drives perform better with regard to energy use than electric drives. However, there are other combinations where the opposite is true. In general, electric drives tend to show a better performance for shorter cycles. One reason for this result lies in the stand-by demand for the electric supply which becomes more important for longer cycles. Furthermore, we can observe that for combinations of small strokes, diameters and longer cycles, pneumatic linear drives tend to have a lower energy demand than electric ones.

In addition to this analysis of the baseline, we conduct a brief sensitivity analysis to gain a better understanding of the impact of uncertainties with regard to the determination of energy demand. For this purpose, we assume that the demand of the pneumatic drives is halved in one case (Figure 4, middle) and doubled in the other case (Figure 4, right). As expected, the performance of pneumatic drives becomes better for shorter cycles and larger diameters in the former case. In the latter case, the opposite effect can be observed.

Starting from these results for the baseline, we now address the individual cases (Figure 5). The results for case 1 show that pneumatic drives become more favourable with an increase in holding time. This improvement mainly concerns cycles with

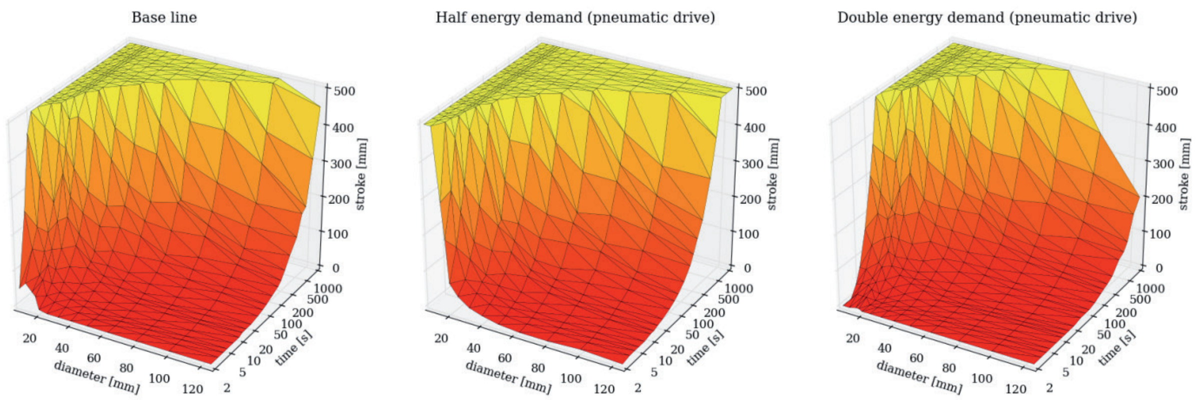

Figure 4. Sensitivity analysis of the energy demand for the baseline.

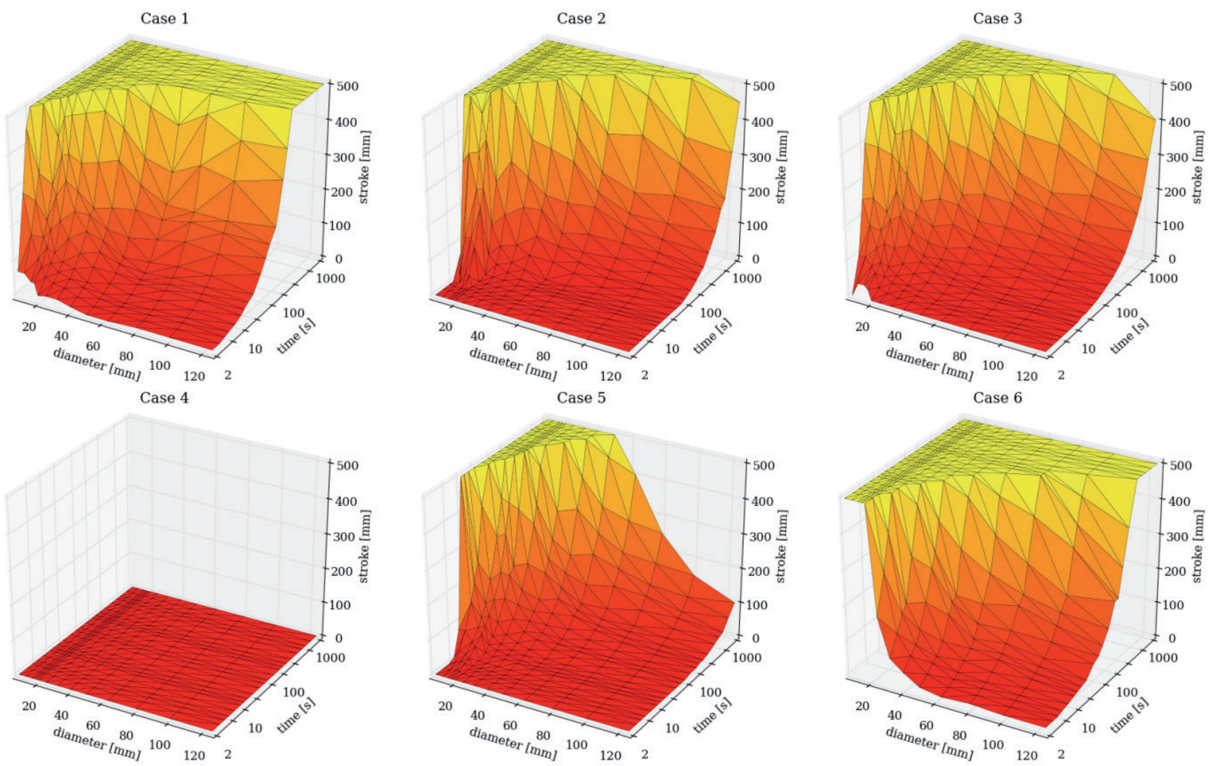

Figure 5. Results of the energy comparison.

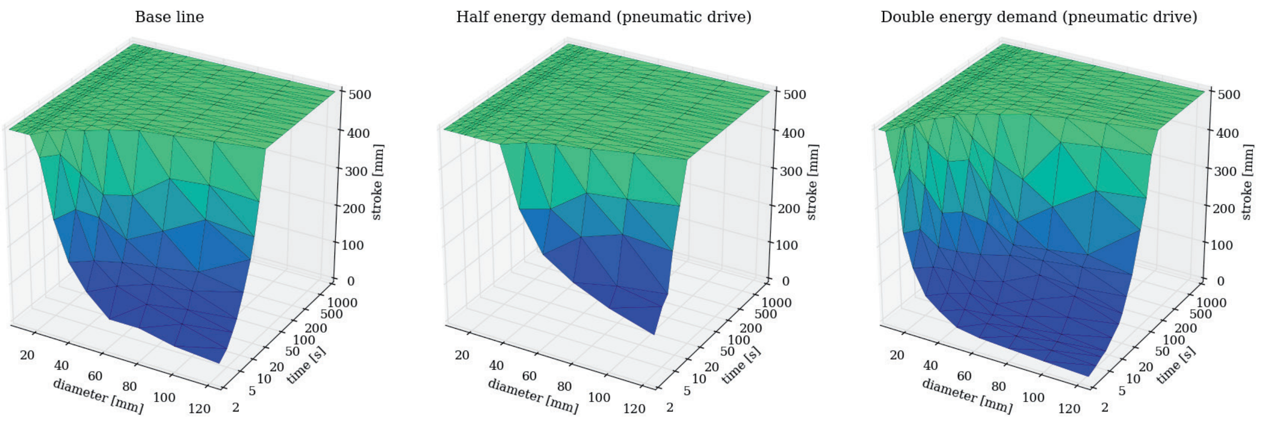

Figure 6. Sensitivity analysis of the comparison of cost for the baseline.

a longer duration, as longer cycles also mean a longer holding time. A longer piping in case 2 shows that the piping is especially crucial for cylinders with small diameters that have short cycles. Adding a small leakage to the analysis in case 3 only slightly affects the results of the comparison. Larger leakages (case 4), however, can easily offset any energetic advantages of pneumatic drives as compared to electric ones. Similarly, the reduction of electric stand-by considerably shifts the results in favour of electric linear drives (case 5). Then, only small cylinders with longer cycles remain better than electric drives. Finally, we can observe that the heat recovery positively affects the results for pneumatic drives (case 6). However, electric cylinders with larger diameters and shorter cycles still show a better performance than corresponding pneumatic drives.

RESULTS FOR COSTS

After the preceding analysis of energy demand, we now proceed to the comparison of costs (Figure 6, left). Again, we can observe that there are situations where electric drives perform better and other situations where they perform worse than pneumatic linear drives. As a general observation, the results become more favourable for pneumatic drives as they have lower investments.

In the sensitivity analysis, we only modify energy demand and leave investments unchanged. If the demand of pneumatic drives was cut by half (Figure 6, middle), they would become favourable for many combinations of stroke, diameter and cycle times with the exception of very large diameters, short cycles and long strokes. If the pneumatic drives used twice the energy (Figure 6, right), pneumatic drives would still remain advantageous for many combinations though electric drives would gain in performance especially with regard to small diameters and longer cycles.

Based on this analysis of the baseline, we proceed to the different cases (Figure 7). As the sensitivity analysis already implies, pneumatic drives tend to perform better within the comparison of costs as compared to the results concerning energy demand. Due to the comparatively important role of investments, there are only small changes for cases 1 to 3. Note that despite the detrimental effects of leakages on the energy performance of pneumatic drives, their impact on the comparison with regard to costs is far smaller (case 4). The same is true for the reduction of electric stand-by (case 5) and the effect of the heat recovery (case 6). The latter can be mainly explained by the lower gas price as compared to electric energy.

When it comes to the remaining three cases, we can observe that the reduction in annual operating hours favours the pneumatic drives as the investments become more important (case 7). A prolonged lifetime, on the contrary, has the opposite effect (case 8). And finally, the considerable reduction in investments for electric drives clearly makes them more favourable. This is especially true also for smaller diameters as long as the cycle time does not become too long (case 9).

Discussion

The results of our analysis indicate that there are cases where pneumatic linear drives outperform electric alternatives with regard to energy demand and costs, and there are in turn other cases where electric drives show a better performance. Thus, our results underline that generalizing statements on the performance of electric and pneumatic drives can be misleading. Nevertheless, we can observe a trend that electric drives tend to be more favourable for shorter cycles, larger diameters and longer strokes with regard to energy demand and costs. Pneumatic drives, on the contrary, are preferable for longer cycles, smaller diameters and shorter strokes.

With regard to the limitations of the results and method in general, note that our concept is aimed to illustrate configurations with equal energy demand or costs. Thus, we only provide statements in terms of better and worse, but we do not analyse the intensity of differences. Nevertheless, differences can grow considerably above or below the plane. This is to a certain degree visible in the sensitivity analyses for the baseline. There, we illustrate how the plane would change if energy demand was modified by a factor of two. Note further that attributing investments for the upstream compressed air system to the pneumatic drives via a mark-up on the electricity price is only one possible way of including the corresponding investments in the analysis. There might be situations where it is not necessary at all to include them and there are other situations where entire parts of the supply systems would have to be considered for the comparison.

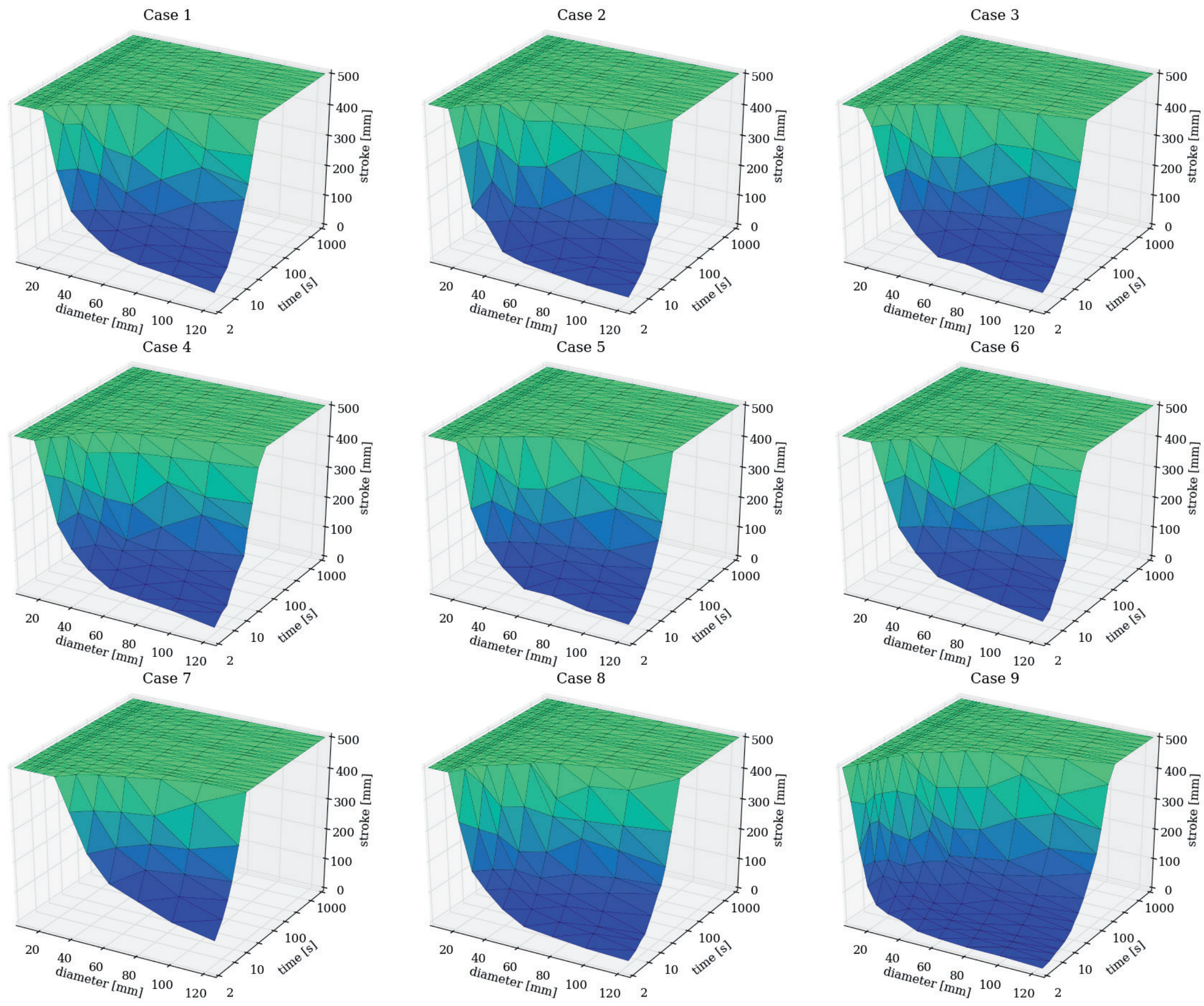

Figure 7. Results of the cost comparison.

Due to the general nature of our analysis, assumptions are necessary and uncertainties are therefore inevitable. In this regard, it is necessary to stress that we selected specific types of drives for the comparison. Furthermore, we used input data from an idealized comparison of technological performance parameters. Changing the drives, modifying technological parameters or introducing measures to reduce energy demand (e.g. Harris et al. 2012; Gauchel 2006) can considerably affect the energy demand and thus alter the results of the comparison. In practical applications, it is likely that the selection of drives is based on other factors as well. Thus, it is unlikely that decision-making regarding the selection of pneumatic or electric drives will only depend on energy demand and costs. Such other factors are not included in our analysis, but they also have to be taken into consideration. Finally, it has to be mentioned that data on the costs and lifetimes of drives and add-on components are subject to considerable uncertainty due to the large number of different technological solutions and prices.

Despite these limitations, we think that our method and illustration allow providing a broader view than other case studies on the comparison of electric and pneumatic linear drives. Thus, they provide a better understanding of the impact of certain parameters on the comparison of both types of drives.

Conclusions

In this paper, we conducted a structured comparison of pneumatic and electric linear drives with regard to their energy efficiency and costs. For this purpose, we introduced a simple framework for comparing both types of drives and we systematically analyzed the impact of varying framework conditions on the comparison. To illustrate the results, we suggested a three-dimensional visualization based on equal energy demand and costs.

Despite various uncertainties related to the analysis, our results clearly indicate that from the point of view of energy demand and costs, no general statements can be given whether to best use pneumatic or electric linear drives. Of course, there is a need for further investigations, but it seems misleading to choose linear drives based on generalizing statements about the efficiency of compressed air systems. It is rather advisable to identify the most suitable technological solution based on the requirements of the individual applications and under the consideration of the specific framework conditions.

With regard to future research, it would be interesting to extend the analysis to other types of drives (e.g. direct drives, belt drives) and technological parameters (i.e. movement profiles). Another option for further development consists in explicitly considering the impact of environmental requirements such as the costs for adapting the drives to these requirements (e.g. additional encapsulation) or their impact on the drives' lifetime. To allow for a more general conclusion, it would also be relevant to collect more detailed empirical assessments of the use of drives (cycle times, types of drives) to provide a differentiated view of aggregate energy-saving potentials and to estimate the impact of specific approaches to reduce energy demand (e.g. switching drives off, compressed air recycling, recovery of electric energy). And finally, an important issue to be investigated is the actual decision-making behaviour for selecting drive technologies. It remains largely unknown how factors such as complexity of the drives, their flexibility and robustness affect technology selection and how they relate to criteria such as costs and energy demand.

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