FRAUNHOFER INSTITUTE FOR CHEMICAL TECHNOLOGY ICT

STUDY ON THE ENERGY-SAVING POTENTIAL OF ELECTRIC MOTORS WITH VARIABLE-SPEED DRIVES IN THE EUROPEAN UNION

Final Report

offen

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Index of Abbreviations

avg	Average
e_{save}	Real energy saving potential
e_{total}	Total energy saving potential
e_{unit}	Energy saving potential per unit
HVAC	Heating Ventilation Air Condition
GHG	Greenhouse-gas
GW	Gigawatt
kg	Kilogram
kW	Kilowatt
n_{sold}	Number of sold units
P	Power
$p_{install}$	Installed Power
pot_{exist}	Existing VSD market potential
pot_{VSD}	VSD market potential
sh_{exist}	Share of existing VSDs
sh_{var}	Share of variable flow applications
TWh	Terawatt hours
VSD	Variable speed drive

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1 Executive summary

Using variable speed drives for electric motors in industrial applications with a variable speed profile can lead to significant energy savings. This is especially common in applications that have a cubic power increase with the rotational speed, like pumps, fans and compressors. These units can save a disproportionately high share of energy by lowering the rotational speed of the unit in reduced flow operation conditions.
The energy saving potential of these applications in the European industry is investigated and quantified in this study.

The main results of the study are:

- **Per unit**, average savings between **10 % and 75 %** are possible. The different saving potential depends on the specific application and load cycles.
- Looking at the individual applications across the entire market, the average saving potential is between 2 % and 30 %. These savings are lower than the theoretical savings per unit because:
  - Not every application is suitable for VSD usage. There are constant flow applications that do not benefit from a VSD.
  - Many VSD units are already in use in Europe. These are not accounted for future energy savings.
- The total savings potential for all three applications (pumps, fans, compressors) is **121,1** TWh/year or 9 % of the annual electric motor consumption in the EU (Figure 1):
  - Pumps: **36,0** TWh/year (15 % of consumption pumps)
  - Fans: **70,3** TWh/year (29 % of consumption fans)
  - Compressors: **14,8** TWh/year (4 % of consumption compressors)
- These **121,1** TWh/year can be saved in addition to the **41** TWh/year that are already saved today by using VSDs.
- The saving potential corresponds to the annual energy production of 6,9 coal power plants with 2 GW electric power. It is greater than the total energy produced by all ignite power plants in Germany in 2022 [1].

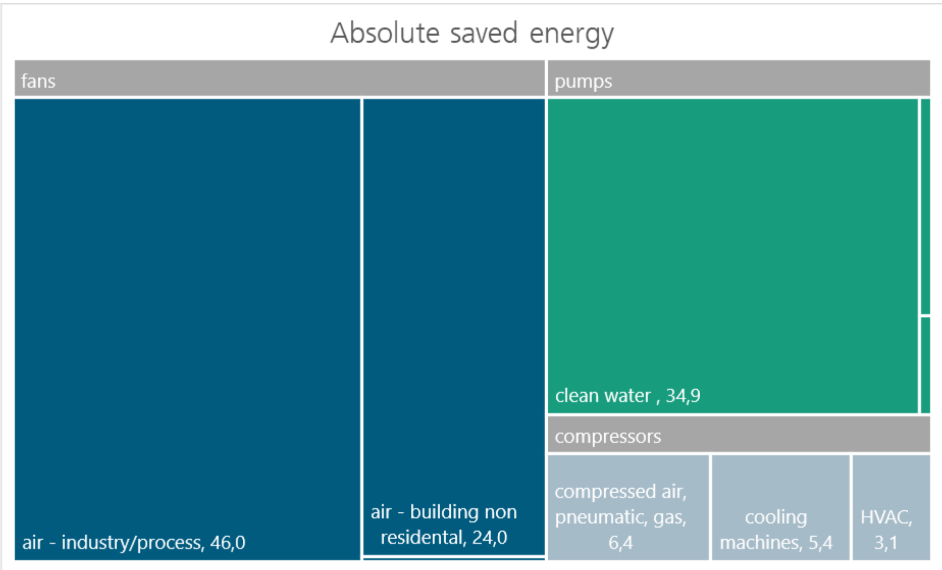

Figure 1: Energy saving potential by using VSD for variable flow applications

2 Introduction

In Europe, 46 % of all electrical energy is used by electric motors [2]. Of this, 70 % is consumed in pump, fan and compressor applications. The total power of the annually sold units of these three applications alone is estimated to be 101,3 GW. The remaining 30 % of energy of electric motors is used to drive conveyors or other systems for material handling and processing [3].

Applications like pumps, fans and compressors often operate in partial load. The reduction in mass-flow is often achieved by mechanical flow controls like throttle valves, bypasses, and dampers. Such flow controls systems lead to high energy losses. Alternatively, variable speed drives (VSD) can be used to reduce flow. VSDs vary the motor speed and consequently also the mass-flow. As the power demand of these applications grows approximately cubic with the mass-flow, even small reductions in the rotational speed result in high savings of consumed energy [3].

For a typical pump application around 45 % of energy can be saved by using VSD in part-load operation [4]. According to [5], the energy savings when driven by a VSD are 25 % to 50 % for typical fan applications and 15 % to 20 % for typical compressor applications. In constant torque applications like conveyors, the energy savings are linearly proportional to the speed reduction [5].

The scope of this study is the quantification of the energy saving potential of electric motors that operate under variable load conditions and can be driven by a VSD. The focus will be on pump, fan and compressor applications in the European market.

Firstly, the calculation methods will be explained. After that the different influences on the energy saving potential of the pump, fan and compressor applications are explained. Also, the overall energy saving potential is presented. At the end some approaches for market surveillance strategies are given to achieve a higher share of VSD and thus the energy savings in reality.

3 Methodology

For the calculation of the energy savings potential a workflow is implemented and applied, see Figure 2. The individual steps are explained in the following chapter.

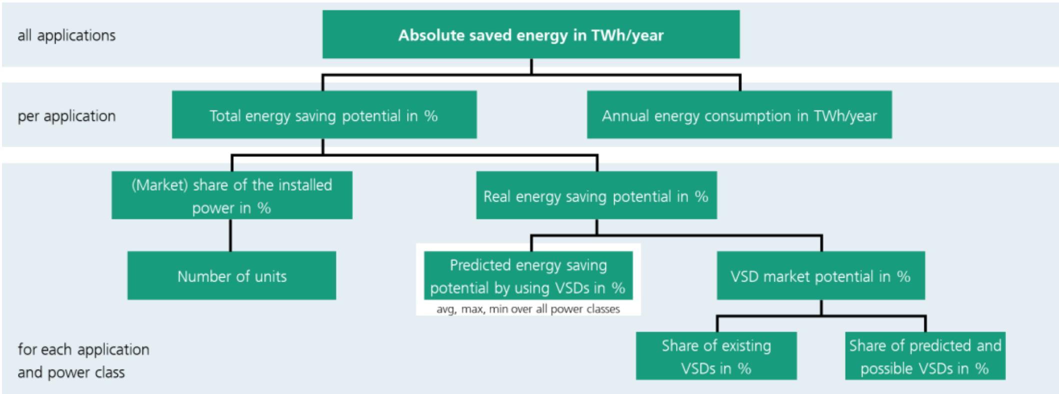

Figure 2: Workflow for determining the absolute saved energy by using VSDs

3.1 Market allocation

As mentioned in the introduction, the main areas of application for industrial electric motors in Europe are as follows: [3]

- Pumps
- Fans
- Compressors (refrigerant and compressed air)
- Conveyors
- Other (material processing and handling)

Pumps, fans and compressors in variable flow applications are particularly suitable for drive with VSDs due to the high savings potential. The market segments are broken down even further below to calculate the savings potential more precisely. According to [2], [4], [6] and [7], the following applications and their subclasses have been identified for the saving calculation:

- Pumps:
  - Clean water pumps:
    - Drinking water
    - Building pressure booster
    - Swimming pool
  - Pumps for heating and cooling applications
  - Sewage pumps
    - Wastewater (liquid)
    - Slurry pumps and wastewater pumps containing solids
  - Oil pumps:
    - Hydraulic
    - Pipeline
  - Chemistry applications
- Fans:
  - Air:
    - Building (non-residential)
    - Industry

  - Refrigerant applications
- Compressors
  - Refrigerant applications:
    - HVAC (heating, ventilation and air condition)
    - Industrial cooling
  - Compressed air, pneumatic, gas

In addition to the division into applications, the power class of the motors is also important for the calculation. The power classes of motors in accordance with the EN 50347 [8] standard are listed in the following Table 1.:

Table 1: Electric motor standard power classes according to EN 50347

power classes from DIN EN 50347 in kW									
0,37	0,55	0,75	1,1	1,5	2,2	3	4	5,5	
7,5	11	15	18,5	22	30	37	45	55	
75	90	110	132	160	200	300	450	750	1300

Every datapoint or calculated number can then be assigned to a combination of a specific application and power class.

3.2 Application quantification

From different references, mostly preparatory studies for EU regulations, the sold number of units for the different applications are collected. In most references the sold units for a specific product type are given with an average power for different power ranges. This enables the clustering in the power classes.
Some market numbers are from earlier years. To have the same year data for all the applications, the market data is extrapolated to the year 2020 with market growth values. The growth values are often given in the reports.

The distribution of sold numbers over the power within an application can vary. In one application there can also be many units with low power or some high-power units.
Also, the VSD market potential (see chapter 3.3) can vary within an application with the power.

To take into consideration the power dependence of the VSD market potential, the market share of the installed power of the sold units p_{install} is calculated. This is the product of the sold units n_{sold} times the power P, divided by the sum of this value for all the applications. It is shown in the formula below:

$$p_{install} = \frac{n_{sold} \cdot P}{\sum n_{sold} \cdot P} \qquad (1)$$

With this number, the energy consumption distribution over the power within an application can be estimated.

3.3 VSD market potential

The VSD market potential is determined as a correction factor that takes into consideration the real market situation for the different applications. The predicted energy saving potential for the several units is reduced by this factor.
A certain share of the several applications operates with constant flow. Although it is also possible to save energy with VSD in constant flow applications the saving potential

per unit is lower (chapter 8.1). Besides that, the goal of this study is the investigation of the energy savings in variable flow applications.

Already today, a certain share of variable flow applications is operated with VSDs. The savings from these units are not counted in the future energy saving potential.

The share of variable flow applications (sh_{var}) and the share of already existing VSD units within the variable flow applications (sh_{exist}) are multiplied to calculate the VSD market potential $\mathbf{pot_{VSD}}$:

$$pot_{VSD} = (1 - sh_{exist}) \cdot sh_{var} \qquad (2)$$

3.4 Quantification of energy savings potential

After the market has been analyzed on the basis of sales numbers, share of installed power and VSD market potential, the energy saving potential is calculated.

3.4.1 Energy saving potential

The unit-wise energy saving potential for the several applications is calculated. Scientific research is done, to find as much references as possible for the different applications.
In the most references, the energy consumption of an example system with and without VSD is measured or simulated. The share of saved energy is filled into the table for the different applications.

Depending on the individual systems and their specific load profile, the share of saved energy can vary, even within an application. To handle the different datapoints, the average saving value from all references within one application is calculated, the so-called "predicted energy saving potential by using VSD".
For every application the minimum and maximum value are given too. Thus, a range of saved energy can be calculated, also to give an estimation of possible variation.

At the end there is one minimum, maximum, and average for every application, with no distinction in the power classes. This is justified with the assumption, that the share of saved energy is scalable with the affinity law.

This predicted energy saving potential by VSD $\mathbf{e_{unit}}$ is then multiplied with the VSD market potential $\mathbf{pot_{VSD}}$ from chapter 3.33.3. This reduces the energy saving potential, depending on the specific characteristics of the individual application. The explanation is given in chapter 3.3 and in the following chapters for the several applications. The result is the real energy saving potential e_{save}.

$$e_{save} = pot_{VSD} \cdot e_{unit} \qquad (3)$$

The final goal is, to have a share of saved energy for every application, which can be used to calculate the absolute saved energy.
Therefore, the power dependent share of installed power (chapter 3.3) and the real energy saving potential e_{save} are matched. This is done by calculating the sum-product of these two values over the power classes (equation (4)). The result is the total energy saving potential $\mathrm{e_{total}}$ which is the share of saved energy for every application, with a minimum, average and maximum value. It matches the predicted energy saving potential per unit with the real market conditions.

$$e_{total} = \sum_{powerclass} p_{install} \cdot e_{save} \qquad (4)$$

3.4.2 Absolute saved energy

With the total energy saving potential, the absolute value of saved energy in TWh/year is calculated.

Therefore, the overall electric motors energy consumption is taken from references. From references it is possible to get the overall energy consumption for pumps [4], fans [7] and compressors [9–11].
The relative energy consumption within the several applications is calculated from the sub-application specific references. This share is then multiplicated with the energy consumption for the application class, resulting in a total energy consumption for every sub-application.

The absolute saved energy is then calculated by multiplying the consumed energy with the total energy saving potential application-wise.

3.4.3 Already saved energy

The energy that has been saved already by using VSD in variable flow applications is estimated. Therefore, the same workflow as before is applied. The only difference is the calculation of the VSD market potential (equation (5)). For the already reached savings it is calculated by considering only the existing share of VSD within the applications. The methods for the remaining workflow are the same.

$$pot_{exist} = sh_{exist} \cdot sh_{var} \qquad (5)$$

4 Pump applications

As described in chapter 3, the following pump applications are investigated:

- Pumps:
  - Clean water pumps:
    - Drinking water
    - Building pressure booster
    - Swimming pool
  - Pumps for heating and cooling applications
  - Sewage pumps
    - Wastewater (liquid)
    - Slurry pumps and wastewater pumps containing solids
  - Oil pumps:
    - Hydraulic
    - Pipeline
  - Chemistry applications

Within the research, no market data for pumps in oil and chemistry applications have been found. That's why they are excluded in the further investigations.

4.1 Quantification and VSD market potential

4.1.1 Market data and installed power

The sales figures for pumps are mainly taken from the preparatory study for the pump ecodesign regulation [4]. The study aims mostly on pumps for clean water and wastewater applications. Numbers for pumps in heating and cooling applications are estimated from [12].
The numbers are illustrated in Figure 3. In 2020, the number of pumps in scope are estimated to 2,6 million units. 63 % of the sold units are clean water pump, followed by swimming pool pumps and wastewater pumps. When looking at the installed power (Figure 4), the share of clean water pumps is similar to the share of the sold units (Figure 3). The share of installed power for wastewater pumps and building pressure booster roughly doubles, compared to the share of sold units. For swimming pool pumps, the share of installed power is lower than the share of sold units (7 % to 24 %).

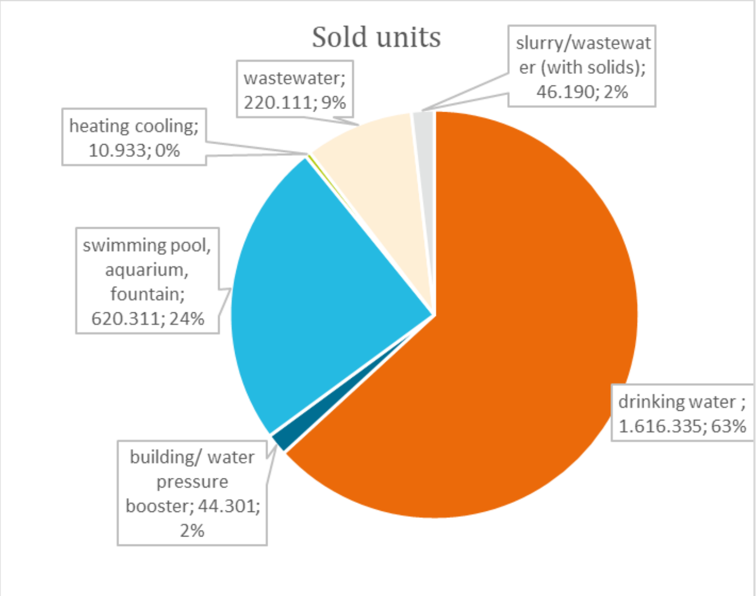

Figure 3: Market share of pump applications in number of sold units, 2020

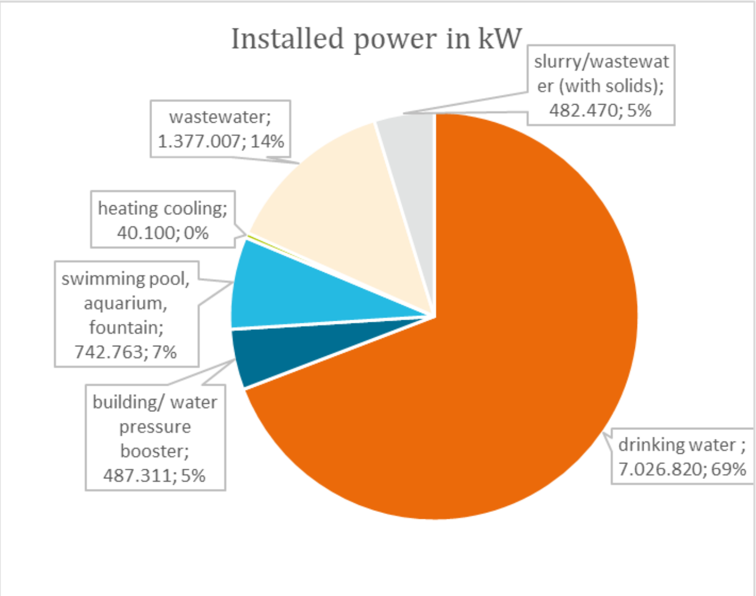

Figure 4: Market share of pump applications in total power, 2020

4.1.2 VSD market potential

The VSD market potential for pump applications is shown Table 2Table 2. The numbers are explained in the following chapter.

For drinking water pumps, building pressure booster sets and pumps in heating and cooling application, the VSD market potential is between 10 % and 50 %. Depending on the specific application and the power class, 50 % to 100 % of units are variable flow applications that can run with VSD. Of 10 % to 20 % of these units already have a VSD installed. [4]

The load cycle of swimming pool pumps is determined by the turnover rate of the pool volume. The pool water volume must flow through the filter in a defined time. This leads to only constant flow applications and within a VSD market potential of 0%. Energy savings by VSD for constant load applications are not in scope of this study and not taken into consideration for the following calculations. They are addressed in chapter 8.1 as part of the additional benefits.
In other countries the share of variable flow applications can vary, due to different hygienic regulations. [4]

Many wastewater pumps operate at constant speed, due to the typical load cycles. An example is, to pump off a sewage reservoir in a certain time. Also, these pumps often must handle water with solids particles, which can cause a clogging of the pump at low flow rates. These functional requirements limit the share of variable flow applications. Also, the most variable flow applications already use VSDs for flow control, that explain the already achieved savings for these applications (chapter 7.3). [4]
The functional constraints result in a VSD market potential of 0 %.
According to the reference [4], a not quantifiable number of users might switch from a constant flow system to variable flow system, if the function is ensured and clogging of the pump can be excluded.

Table 2: VSD market potential for pump applications

power classes from DIN EN 50347	pumps					
	clean water				sewage	
	drinking water	building/ pressure booster	swimming pool, aquarium, fountain	heating / cooling	wastewater (liquid)	slurry/ wastewater (with solid)
0,37				46 %		
0,55				45 %		
0,75			0 %	44 %		
1,1	37 %			43 %		
1,5				42 %		
2,2				41 %		
3	47 %			40 %		
4	45 %			39 %	0 %	
5,5	46 %			38 %		
7,5				37 %	0 %	0 %
11				36 %		0 %
15				35 %	0 %	
18,5				34 %		
22		50 %		34 %		
30	38 %			33 %	0 %	
37			0 %	32 %		0 %
45				32 %		
55				31 %		0 %
75	15 %			30 %	0 %	
90				29 %		
110				29 %		0 %
132				28 %		
160				28 %		0 %
200	10 %			27 %		
300				26 %		
450				25 %		
750				23 %		
1300				21 %		

4.2 Quantification of the energy savings potential

The references used in the calculation of the predicted energy saving potentials are as follows:

- Clean water pumps:
  - Drinking water [4, 13–19]
  - Building pressure booster [4], [20], [21], [22]
  - Swimming pool
- Pumps for heating and cooling applications [21], [22], [23], [24]
- Sewage pumps
  - Wastewater (liquid) [4], [25]
  - Slurry pumps and wastewater pumps containing solids [4]

In the boxplots (Figure 5), the distribution of the unit power saving potential from the references for pumps in drinking water, building and heating/cooling applications is shown.

Drinking water pumps can save 44 % in average, when driven by a VSD. This average is near of the maximum value of 49 %, which means that most units are in the range of the average and maximum savings. In rare cases lower savings of 23 % are possible for individual units.

For pumps in building pressure booster applications, the most datapoints are in the range of the average value of 49 %. Higher savings up to 64 % but also lower savings of 28 % are possible for individual units.

According to the references, the maximum savings of pumps in heating and cooling applications are 98 %. These values are very high, the average is much lower at 76 %. The minimum saving value found in this application is at 45 %.

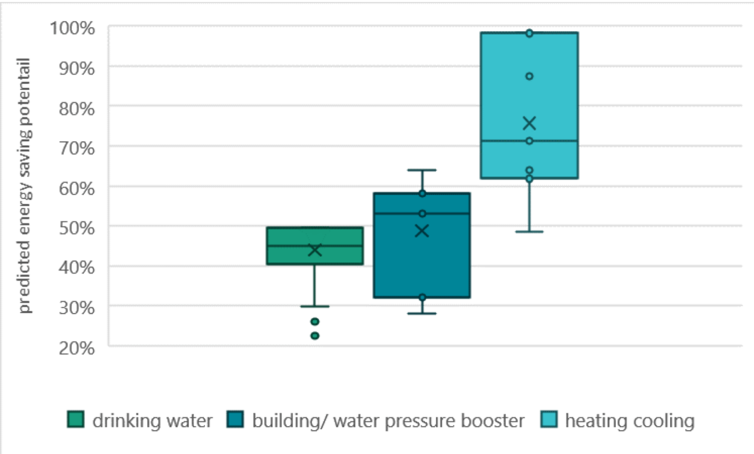

Figure 5: Predicted energy saving potential by using VSDs for pumps in drinking water, building and heating/cooling applications

The minimum, maximum and average values of the predicted energy saving potential and the total energy potential, are shown in Table 3.
Considering the VSD market potential, the total energy potential of swimming pool pumps and wastewater pumps is 0 %. The main reason is the high share of constant flow applications, which is explained in chapter 4.1.25.1.
The VSD market potential for pumps in drinking water, building and heating/cooling applications is between 20 % and 50 %. This means a reduction of the energy saving potential to this proportion. The average total energy saving potential is 18% for dink-ing water pumps, 24 % for building pressure booster and 28 % for pumps in heating and cooling applications.

Table 3: Predicted energy saving potential and total energy saving potential for pumps

		pumps					
		clean water			heating/ cooling	wastewater	
		drinking water	building/ water pressure booster	swimming pool, aquarium, fountain		wastewater (liquid)	slurry/ wastewater (with solid)
Power saving potential per unit	average	44 %	49 %	0 %	76 %	44 %	45 %
	min	23 %	28 %	0 %	45 %	37 %	45 %
	max	49 %	64 %	0 %	98 %	46 %	45 %
Total energy saving potential (with VSD market potential)	average	18 %	24 %	0 %	28 %	0 %	0 %
	min	9 %	14 %	0 %	17 %	0 %	0 %
	max	20 %	32 %	0 %	37 %	0 %	0 %

5 Fan applications

According to the references, fans in the following applications are investigated:

- Air ventilation
  - Non-residential building
  - Industry
- Refrigerant applications

5.1 Quantification and VSD market potential

5.1.1 Market data and installed power

The numbers of sold units for the non-residential building fans and the industry fans are taken from the preparatory study for the fan ecodesign regulation [7].
The source numbers are from the year 2005, an estimation to 2020 is done with an average market growth rate of 3,5 %. 72 % of the market units are fans for industry applications, 28 % for non-residential building ventilation (Figure 6). With 73 % and 27 %, the share of installed power is nearly the same as the share of units (Figure 7).

The number and average power for the fans in refrigeration units are taken from [12]. Compared to the other fan sub-applications, their share of sold units and installed power is smaller than 1 %.

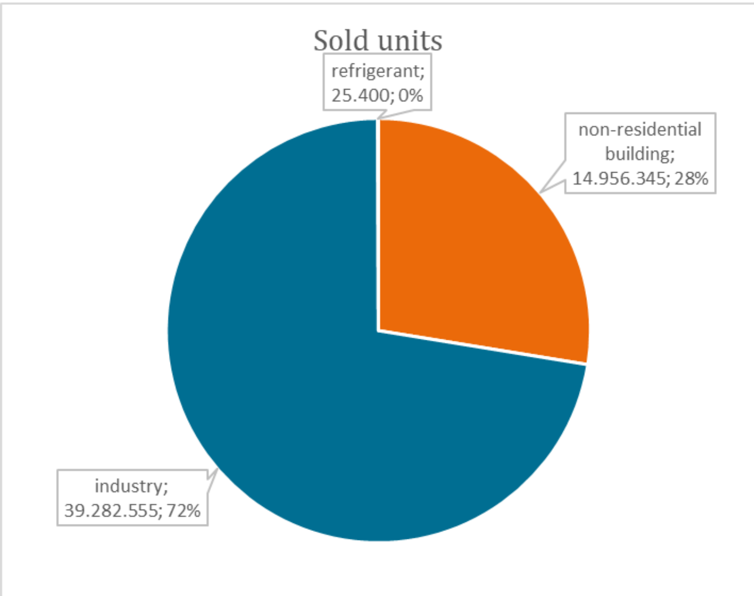

Figure 6: Market share of fan applications in number of sold units, 2020

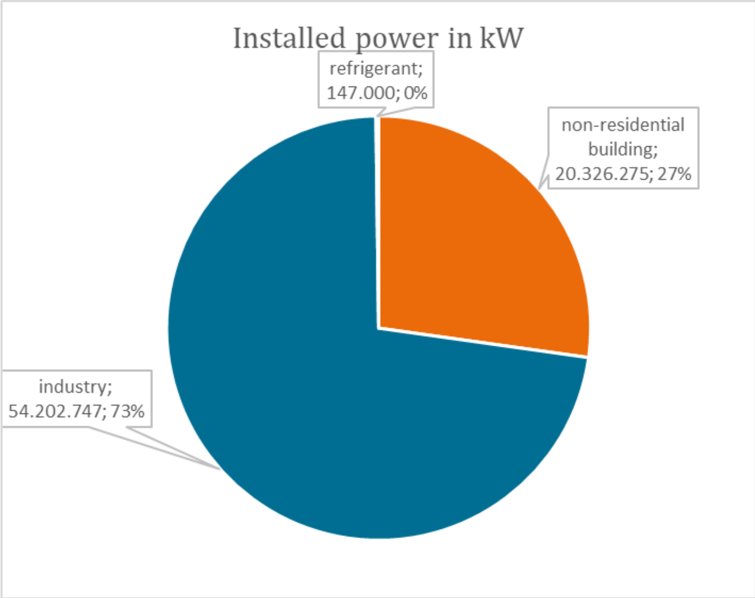

Figure 7: Market share of fan applications in total power, 2020

5.1.2 VSD market potential

[26] estimates the share of theoretical possible VSDs to 60 % for fans in industry and building applications and to 30 % in refrigeration applications.
No fan-specific data has been found for the share of already existing VSDs, instead the share of VSDs for all electric motors is used. It is estimated from 1 % to 54 % for 2020, depending on the unit power [27], [28].
With these numbers, the VSD market potential for the fan applications is calculated. It is presented in Table 4. For building and industry ventilation applications the VSD market potential is between 59 % and 28 %, for refrigerant applications between 30 % and 14 %.

Table 4: VSD market potential for fan application

		fans		
		air		refrigerant
		non- residential building	industry	
power classes from DIN EN 50347	0,37	59 %	59 %	30 %
	0,55	58 %	58 %	29 %
	0,75	57 %	57 %	28 %
	1,1	55 %	55 %	28 %
	1,5	54 %	54 %	27 %
	2,2	52 %	52 %	26 %
	3	51 %	51 %	26 %
	4	50 %	50 %	25 %
	5,5	49 %	49 %	24 %
	7,5	48 %	48 %	24 %
	11	46 %	46 %	23 %
	15	45 %	45 %	22 %
	18,5	44 %	44 %	22 %
	22	44 %	44 %	22 %
	30	42 %	42 %	21 %
	37	41 %	41 %	21 %
	45	41 %	41 %	20 %
	55	40 %	40 %	20 %
	75	39 %	39 %	19 %
	90	38 %	38 %	19 %
	110	37 %	37 %	19 %
	132	37 %	37 %	18 %
	160	36 %	36 %	18 %
	200	35 %	35 %	17 %
	300	33 %	33 %	17 %
	450	32 %	32 %	16 %
	750	30 %	30 %	15 %
	1300	28 %	28 %	14 %

5.2 Quantification of the energy savings potential

The following references have been used to determine the predicted energy saving potential for fan applications:

- Non-residential building fans [29], [30], [22], [31], [32]
- Industry [33], [34], [23]
- Refrigerant [20]

For refrigerant there was only one reference. It estimates the saving for one unit to 10 %. Due to this and the low installed power, the fans in refrigerant applications are not investigated further.
For the other applications the saving potential is between 34 % and 78 % with average values of 57 % in buildings and 59 % in industry fan applications. As illustrated in Figure 8, these values are roughly in the middle between the minimum and maximum

value. Much higher and lower saving values than the average may occur with a higher probability.

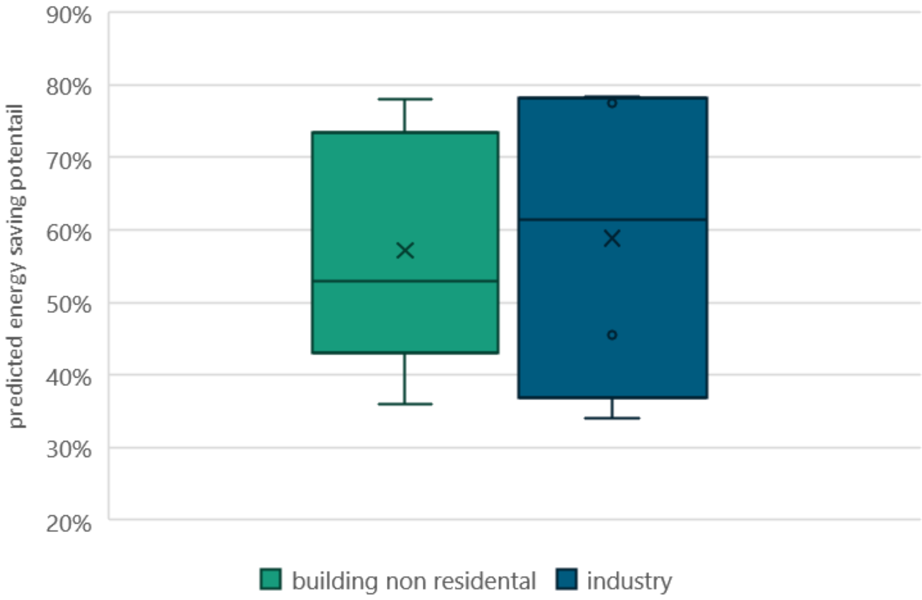

Figure 8: Predicted energy saving potential by using VSDs for fans

In Table 2 the difference between the predicted energy saving potential and the total energy saving potential is shown. Due to the VSD market potential of around 55 %, a total energy of 29 % and 28 % is possible in fan applications. Together with the high installed power and energy consumption this leads to a saving potential of 70,3 TWh/year for fans.

Table 5: Predicted energy saving potential and total energy saving potential for fans

		fans		
		air		refrigerant
		Non-residential building	industry	
Power saving potential per unit	average	57 %	59 %	10 %
	min	36 %	34 %	10 %
	max	78 %	78 %	10 %
Share of saved energy	average	29 %	28 %	2 %
	min	18 %	18 %	2 %
	max	40 %	42 %	2 %

6 Compressor applications

The following compressor sub-applications are taken into account for the calculations:

- Refrigeration
  - HVAC applications
  - Industrial cooling applications
- Compressed air, pneumatic and gas applications

6.1 Quantification and VSD market potential

6.1.1 Market data and installed power

The numbers of sold units are taken from the preparatory studies for the European ecodesign regulations (HVAC [11], industrial cooling [12], compressed air [10]).

The market numbers are shown in Figure 9 and the installed power in Figure 10.
98 % of the sold units are compressors for HVAC applications, but due to the limited power of maximum 12 kW, only 74 % of the installed power of the sold units are from HVAC. For professional cooling and compressed air applications, the share of sold numbers is 1 % each. The power of the units is much higher than for the HVAC compressors, resulting in an installed power of 21 % for the professional cooling machines and 5 % for compressed air.

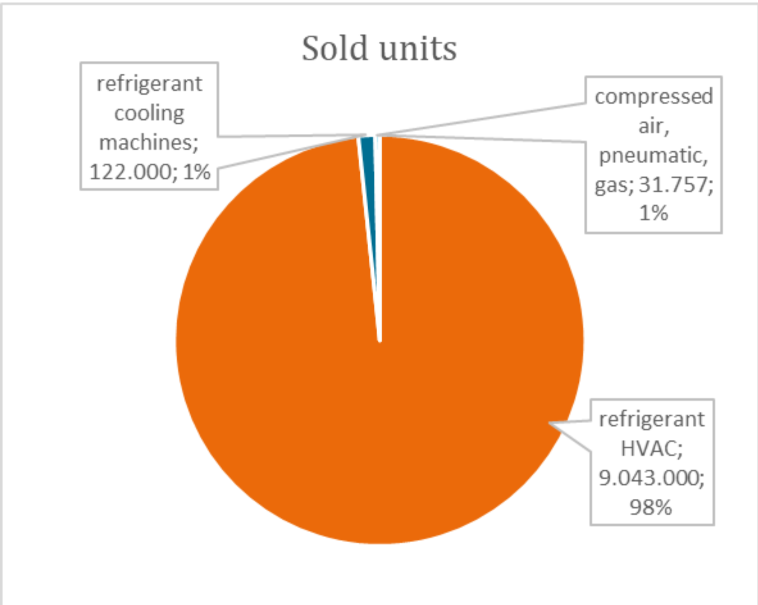

Figure 9: Market share of compressor applications in number of sold units, 2017

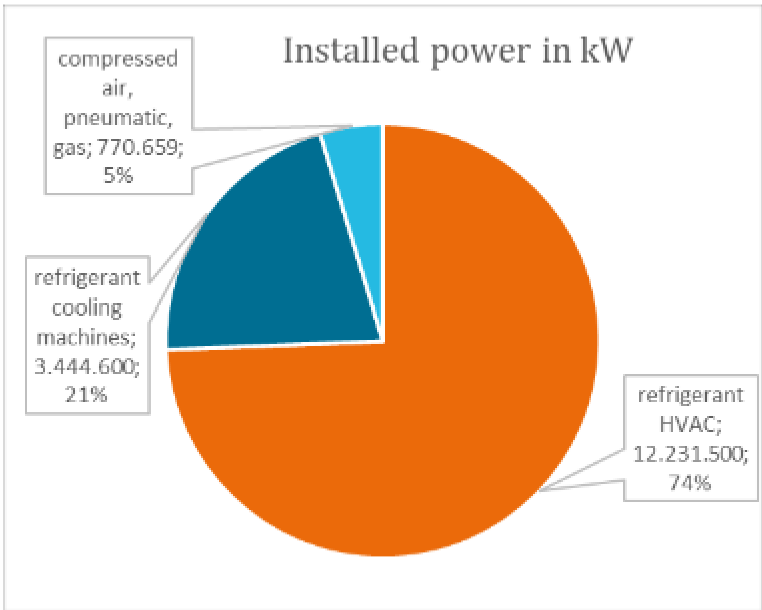

Figure 10: Market share of compressor applications in total power, 2017

6.1.2 VSD market potential

According to [26], 40 % of the HVAC and 30 % of the professional cooling units are suitable for an operation with VSD. The HVAC applications already have a 85 % share of VSD for variable loads [11]. This results in a VSD potential of 6 %.
As share of VSD for professional cooling applications, the share of VSD for electric motors is used. The VSD potential for this application is between 30 % and 14 %

In compressed air applications, 62 % of the applications are suitable for a variable load. Some units already operate with variable load and have a kind of flow control that could be a VSD [10]. As before in the professional cooling, for these applications the share of VSD for electric motors is used. This results in a VSD potential between 29 % and 74 %.

6.2 Quantification of the energy saving potential

The following references have been used to specify the predicted energy saving potential for compressors:

- Refrigerant
  - HVAC [35], [36], [37], [38], [39], [40], [22]
  - Professional cooling [22], [41], [12], [24]
- Compressed air, pneumatic, gas [10], [9], [42], [43], [23]

As shown in Figure 11 for HVAC applications the most units are in the range of 30 % energy reduction. With 53 %, the maximum for this application is much higher than the average. This value seems to be an exception. As described in the chapter before, many VSDs are already in the HVAC market, with a VSD market potential of 6 %. This leads to a total energy saving potential of 2 % (Table 6).

As shown in Figure 11, the unit saving values in professional cooling applications are around 10 %. Values up to 30 % seem to be rare exceptions. The resulting average value for the total saving is at 13 %. The savings are reduced to 3 % due to the VSD market potential (chapter 6.1.2).

Compressor applications

The average savings for compressed air units are 19 %. In the most references the savings are between 10 % and 15 %, some references name higher savings up to 55 %. These seem to be more rare cases. Due to the high VSD market potential with few VSD already in market, the predicted energy saving potential isn't reduced as much as in the other compressor applications. In average the total energy saving potential is 11 %, which is higher than for HVAC and professional refrigeration applications.

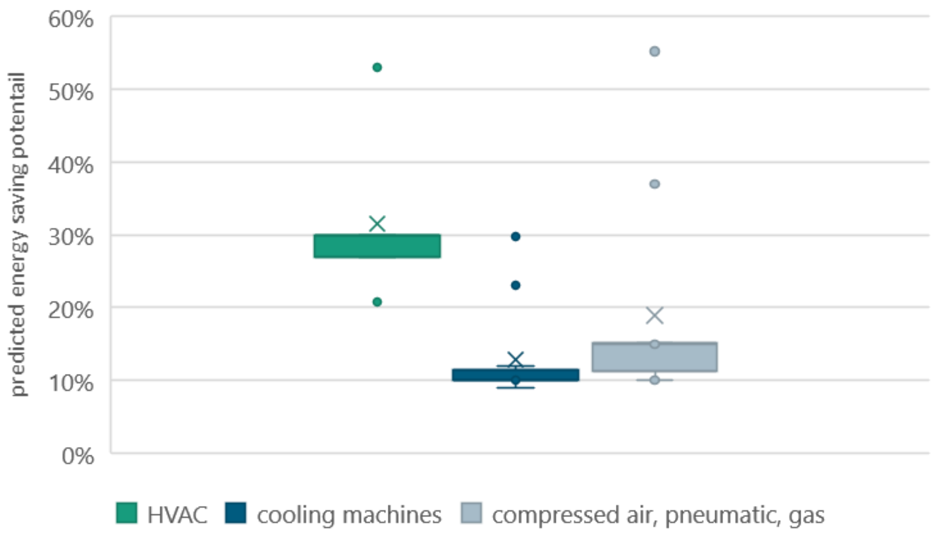

Figure 11: Predicted energy saving potential by using VSDs for compressors

Table 6: Predicted energy saving potential and total energy saving potential for compressors

		compressors		
		refrigerant		compressed air, pneumatic, gas
		HVAC	cooling machines	
Power saving potential per unit	average	32 %	13 %	19 %
	min	21 %	9 %	10 %
	max	53 %	30 %	55 %
Share of saved energy	average	2 %	3 %	11 %
	min	1 %	2 %	6 %
	max	3 %	7 %	31 %

7 Final results: Total energy savings potential

7.1 Energy consumption

The overall electric energy consumption in the EU in the year 2021 was 2 776 TWh [44]. Electric motors consumed 46,3 % of the electric energy, which lead to a consumption of 1 285 TWh.
The energy consumption of the several sub-applications is listed in Table 7 and Table 8.

Table 7: Electric energy consumption of pumps in the EU [4]

	pumps					
Sub-application	drinking water	building/ water pressure booster	swimming pool	heating cooling	wastewater	high solid concentration water
Energy consumption in TWh	197,5	3,2	7,7	1,2	20,8	12,6

Table 8: Electric energy consumption of fans [7] and compressors in the EU [9–11]

	fans			compressors		
Sub-application	non-residential building	industry	refrigerant	HVAC	cooling machines	compressed air, pneumatic, gas
Energy consumption in TWh	82,4	146,8	11,2	161,6	188,2	60,2

7.2 Energy savings potential

Multiplying the energy consumption by the relative savings potential gives the absolute savings potential. The average savings are 121,1 TWh/year which corresponds to 9 % of the annual electric motor consumption in the EU. The saved energy divides into 36,0 TWh/year for pumps, 70,3 TWh/year for fans and 15,1 TWh/year for compressors. These results describe the additional savings potential by retrofitting old systems and equipping new systems with VSDs, which would otherwise be operated on-line and throttled with mechanical valves. The numbers do not include the savings potential of existing and new systems that are already equipped with VSDs anyway. In Table 9 the minimum, average and maximum potential savings of the different applications are listed. The lower half of the table shows the relative share of the savings for each application.

Table 9: Total savings potential by using additional VSDs

Saving in TWh	pumps	fans	compressors	overall
average	36,0	70,3	14,8	121,1
minimum	18,5	41,9	9,2	69,6
maximum	40,6	94,3	36,3	171,2
Share of consumption				
average	15 %	29 %	4 %	9 %
minimum	8 %	17 %	2 %	5 %
maximum	17 %	39 %	9 %	13 %

In references [26, 45, 46] from 2008, the absolute energy saving potential through additional VSDs was determined for the EU15 for 2015. The savings are estimated to be 84 TWh/year in sum for the tertiary sector (21,9 TWh/year) and the industrial sector (61,6 TWh/year). Taking into consideration the different years and the fact that this study examines the entire EU, then the results of this study agree well with the references.

7.2.1 Energy saving for different sub-applications

In Figure 12, the average saved energy for the different applications is shown:

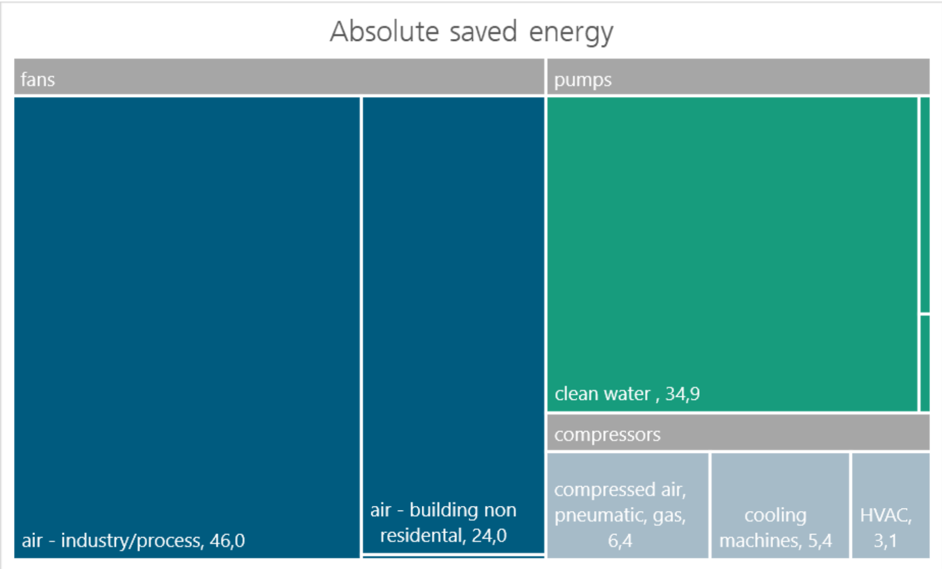

Figure 12: Saved energy of different sub-applications

In the case of pump applications, almost all of the savings potential is attributable to drinking water applications (34,9 TWh/year). They have a high installed power and a high VSD market potential. The pumps for building pressure booster and for heating and cooling applications can save a high share of energy, but due to the small installed power, with 0,8 and 0,4 TWh, the total energy saving values are low.

With 46 TWh and 24 TWh, the air fans for industry and non-residential buildings save the most energy. The share of these values corresponds roughly to the installed power, since the energy saving potentials for both sub-applications are similar. Compared to the other fan application, the 0,3 TWh savings for refrigeration fans are very low.

With 6,4 TWh, compressed air applications have a share of 42 % on the compressor savings, although their energy consumption is only 15 % of the compressor energy consumption. The reason for the high saving is the high (relative) energy saving potential. With 2 % and 3 %, the saving potential for HVAC and cooling compressors is low, but due to the high energy consumption of these applications, the total saved energy reaches 3,1 TWh and 5,4 TWh in average.

7.3 Already achieved savings

With each 10,2 TWh, the savings already achieved by pumps and fans are much lower than the potential savings. This underlines the high future saving potential with VSDs. In compressor applications 21,4 TWh of energy have already been saved by using VSDs. The main part of the compressor savings belongs to the HVAC applications, with 17,3 TWh. The already achieved savings for all applications are shown in Figure 13.

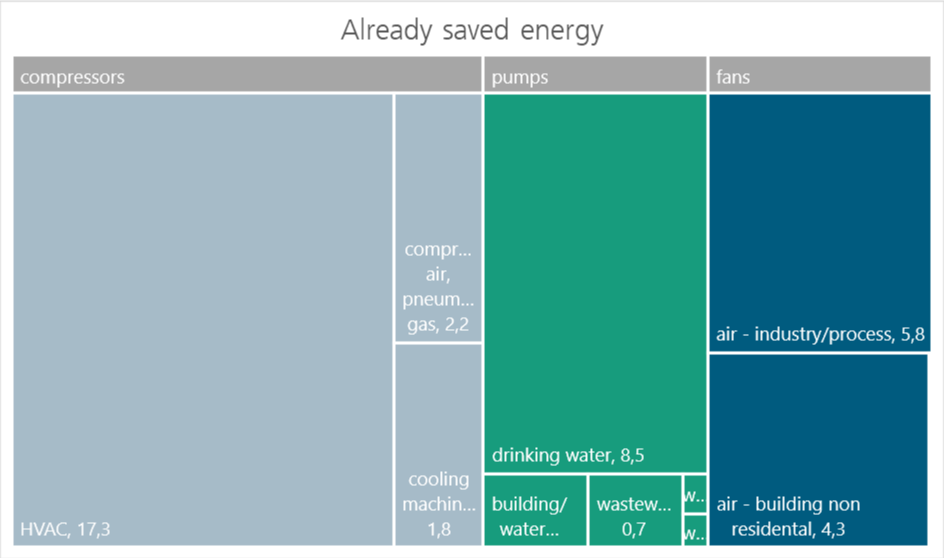

Figure 13: Already reached energy savings by VSDs

7.4 Saving potential in greenhouse gas (GHG) emission

The average emissions of electrical energy in EU are 0,275 kg/kWh of CO_2-equivalent. With the saving of 121,1 TWh/year, the emissions could be reduced around 33 million tons of CO_2-equivalent. This corresponds to 1 % of the annual CO_2-equivalent emissions in the EU.

The 33 million tons of emission reduction are 1,4% of the saving goals, in context of the EU green deal. With the green deal, the EU wants to reduce 55 % of the 1990 GHG emission until 2030, which leads to a saving of 4,4 billion tons of CO_2-equivalent [47].

8 Additional benefits of VSD

Beside the primary goal of saving electrical energy in variable load points, there are other benefits of using VSDs in stationary electric drives.

8.1 VSD in constant load applications

The rotational speed of on-line motors is given by the electrical frequency, the number of poles and the size of the motor. When a certain mass-flow is required, quite often a larger motor than required must be used, which often leads to oversized units.
By applying a VSD, the required mass-flow can be generated by a smaller motor that runs at a higher rotational speed at a better efficiency. For water pump this right-sizing can increase the efficiency around 5 % to 10 %. [4], [6], [48]
VSD measure electrical current and energy consumption, as demonstrated in [49]. By using this data, the user can optimize the pump system to improve efficiency.

8.2 Energy savings beside the electric motor

Energy savings beside the electrical motor are possible in systems, where heating energy is transported with the mass-flow. When the flow is adjusted according to the actual need by a VSD, less heating energy is wasted. Examples are air supply systems for heated buildings or production processes with combustions.
In [29] the demand of heat energy for a school has been reduced by 21 %, by using a VSD with a demand-control for the air ventilation.
In [33] the efficiency of a steam boiler increases by 2,5 % when running the fans with a VSD at a reduced speed.

8.3 Controlling and monitoring

8.3.1 Process improvement

Running an electric motor with a VSD brings also benefits for the production process. With a VSD the motor speed can be adjusted to match the optimal speed of the process, thereby increasing the quality of the process. This is also a benefit for material handling applications. A VSD brings the flexibility to increase the production capacity in the future. Another benefit is the possibility of integrating the drive into the company's industrial network to collect performance data like speed and power. Such applications are suitable for the internet of things or industry 4.0 setups. [6]

8.3.2 Reduced maintenance costs

With a VSD, online measurements of parameters for maintenance operations are possible. Maintenance and diagnostic methods by VSD are presented in [50] for different pump, fan and compressor applications.
In [51] a method for the pressure increase detection of an air filter is presented. The replacement of the filter is triggered when the detected pressure is too high. Other references use the VSD for pollution detection of the fan impellers [52, 53]. Other features are the surge detection in compressors [54] or the estimation of leakage in a compressed air system [55]. [56] shows a bearing fault detection by analyzing the motor current signature.

9 Conclusion and perspectives: Market surveillance strategies for VSDs

As described in the previous chapters, a high amount of energy can be saved by using VSDs in applications, where partial load operation occurs frequently. However, the actual number of VSDs in such applications is lower than it could be, even though the prices for electric energy are high and the electric energy production causes high greenhouse gas emission.
In this chapter strategies to increase the market share of VSDs and consequently reduce the energy consumption of electric motors are discussed. The proposals are to be understood as suggestions. They are not based on in-depth studies of the political or ecological framework conditions.

9.1 Introduction of legal requirements for the general use of VSDs

The technically simplest solution for implementing energy savings through VSDs would be the introduction of legal requirements for the use of VSDs in all newly sold electric motors. It would then not be necessary to introduce complex procedures for assessing energy efficiency, which would greatly reduce the administrative burden for suppliers and manufacturers.
The obvious disadvantage of this approach is that the costs of applications that do not benefit from VSDs would increase. In addition, such a regulation would exclude other technical solutions that could be advantageous in some applications. A high level of political resistance to such a measure is therefore to be expected.
However, such a regulation would be easy to implement in practice. Compliance can be checked just as easily by means of inspection visits to the factories.

As a first step, such a requirement could be restricted to a certain power range to protect low-cost applications from a cost explosion.

9.2 Legal limits for energy efficiency

Another approach would be to introduce a minimum required energy efficiency for the whole drive system, like the NEMA power index [57]. This index also covers the efficiency in partial load points and units with a VSD would benefit from the increased efficiency.
The regulation would make a minimum standard of this energy efficiency index mandatory. System manufacturers must declare this index for the products or the product assemblies, to give a better transparency about the energy consumption of the products.
This regulation approach would be like the efficiency class for electric motors or the energy efficiency class for consumer products.

The advantage is that this index is technology-neutral, as the use of VSDs would not be mandatory. In contrast to the IE class for electric motors, partial load points must be taken into consideration. One disadvantage is that the index would have to be defined for each class of application. There is also a risk of manipulation, for example by using incorrect parameters or load points. To rule out these manipulations, a tight network of independent measurements and tests would have to be implemented, which would, however, require a great deal of effort.

9.3 Legal requirements for the declaration of energy consumption by the manufacturer

This approach is like the energy efficiency index (chapter 9.2). The annual or lifetime energy costs of a product are calculated with a reference load cycle for the application.

This energy costs must be declared for every product group (for example pump + motor + inverter) by the supplier who offers the assembled system. Subsystem manufacturers must deliver the necessary data, like energy characteristic with the product to enable the calculation. By knowing the energy costs, they can be taken into consideration for economical calculations by the owner or user of the system.

The advantage of this approach is that the buyer of the products can decide for the best product with economical standards, without any laws or regulations.
The disadvantages are a high effort for the system providers because they must calculate the energy costs for their different products. It could also be complicated to define a suitable reference load cycle for the different applications.
Another disadvantage is that the energy costs must be paid by the end user. The manufacturer of the equipment, however, tries to minimize his production costs and will not necessarily by more expensive drives.

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