European Commission

Preparatory study

on

Low pressure & Oil-free Compressor Packages

FINAL REPORT

7 June 2017

Prepared by: VHK

contract co-ordination: VITO

Energy

Prepared by

Van Holsteijn en Kemna

Author: Martijn van Elburg, Roy van den Boorn

Quality control: Ulrik Vølcker Andersen | Viegand Maagøe

Date: 7 June 2017, taking into account EC comments of 19 May 2017 on 16 April 2017 version

Project website: www.eco-compressors.eu

Implements Framework Contract: No. ENER/C3/2012-418-Lot1

Specific contract no.: ENER/C3/2012-418-LOT1/10/FV2014-558/SI2.705733

This study was ordered and paid for by the European Commission, Directorate-General for Energy.

Table of Contents

List of Tables

List of Figures

List of Equations

Executive summary

The first DG ENER LOT 31 preparatory study for compressors started in March 2012. Because of the width of the study subject, it was decided during this study to focus on "standard air" compressor packages which were deemed to be most eligible for possible regulatory measures. In that same study "low pressure" and "oil-free" compressor packages were identified as other application ranges possibly eligible for regulatory measures but they could not be analysed in sufficient detail in this first study that was finalised in June 2014.

In the Horizontal Ecodesign Consultation Forum meeting of 5 May 2014 and the Consultation Forum meeting on 23 October 2014, the Commission expressed the intention to study further the eligibility of "low pressure" and "oil-free" compressor packages for possible ecodesign and/or energy labelling measures.

These products are now addressed in this second LOT 31 Ecodesign study on "low pressure" and "oil-free" compressor packages which started on 16 April 2015 and ended on 16 April 2017. The structure of this study follows the MEErP methodology and presents, after an introductory chapter (Preface), seven Task chapters plus six Annexes with supplementary information.

In chapter 1 (Task 1) the scope of the study, product standards and existing regulations are described. The analysis shows that there are product standards available for broadly two groups of compressors (positive displacement and dynamic machines) that allow establishing the main performance parameters, but that these standards are not mutually aligned, which means that performances established using these standards are not directly comparable. The products covered by the scope of the study are not regulated by specific measures in or outside the EU.

Chapter 2 (Task 2) presents data on market and stock, showing overall annual sales of almost 32 000 units in 2015. The rest of this chapter describes the market structure, manufacturers and pricing information, including energy rates.

Chapter 3 describes where and how the products are used, based on the 'extended product approach' which includes consideration of controls. It introduces the concept of flow control categories for structuring the market according customer requirements. It also addresses the larger system in which the products operate and the end-of-life phase.

In chapter 4, the main technologies applied by the products are described. A pivotal part is the section on performance assessment which describes the performances of the average products placed on the market, structured according to flow control category. This assessment is the basis for the calculation of overall energy consumption and savings as presented in the subsequent chapters. Chapter 4 also presents the inputs used for the streamlined life cycle assessment performed in Chapter 5.

Chapter 5 presents the outcome of an environmental and economic assessment, using the Ecoreport tool, which is part of the MEErP methodology. This assessment shows that energy consumption during use is the single largest contributor to most environmental impacts. The overall electricity consumption of the combined low pressure and oil-free products in scope is assessed at 26 TWh in year 2015.

Consequently the Task 6 chapter describes technical options for reducing this impact, ranging from improved package efficiency, to use of VSD's and application of heat recovery. The costs and benefits have been calculated on the basis of total life cycle costs.

In the final chapter 7 possible measures on the basis of the previously identified options are defined, and the impacts, environmental, economic and societal, are assessed in comparison to a business-as-usual scenario. The scenario analysis of these options shows that energy savings achieved through improved package efficiency are typically below 0.4 TWh per year, even if the impact on the market is considerable (up to 40% of sales affected by the measure).

The policy option for increased uptake of VSD-driven equipment resulted in higher savings. The scenario for the option on heat recovery, showed the highest savings. However, specific ecodesign measures can only lower the threshold for (applying) heat recovery, but cannot enforce actual application as this is very application specific and beyond the scope of Ecodesign.

Both measures rest primarily on an awareness raising campaign rather than product specific measures.

In Chapter 7 concludes with a recommendation for the introduction of ecodesign information requirements to harmonize the information on compressor performance, enabling a better comparison of products of various technologies. Resource efficiency requirements, and minimal technical requirements facilitating heat recovery can be added. Introduction of minimum energy efficiency requirements is associated with considerable impacts for 1% of electricity savings and requires further consultation.

A second recommendation is to develop an information and awareness raising campaign similar to the Compressed Air Challenge in the USA, or the EU BUILD UP initiative.

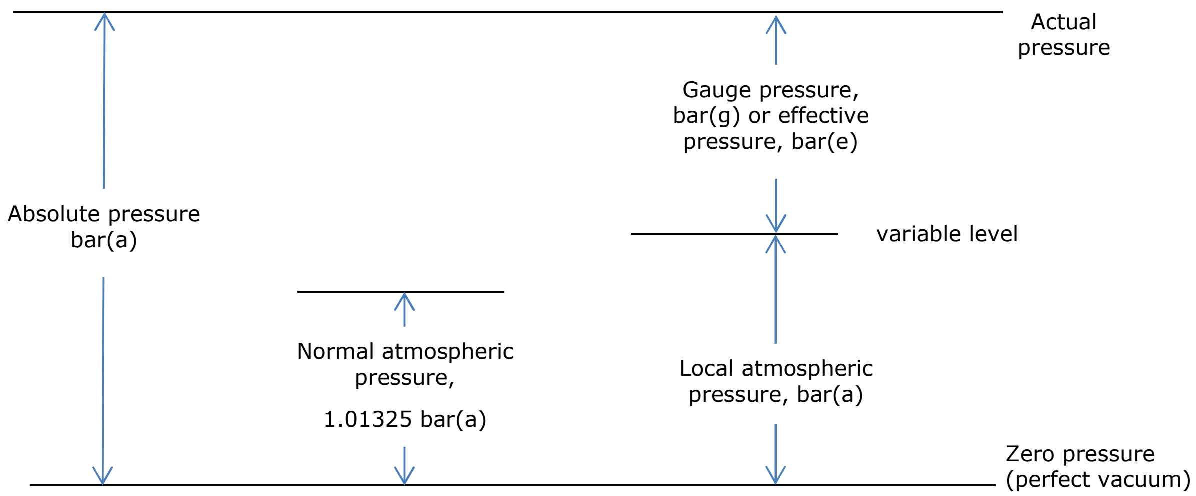
Throughout the study stakeholder consultation was sought through two stakeholder meetings (26 April 2016 and 6 March 2017) and the publication of draft reports, presentations and Minutes of meetings on the publicly accessible study website.

Acronyms, terminology and symbols

a	year (annum)
absolute pressure	pressure measured from absolute zero i.e., from an absolute vacuum. Gauge pressure plus ambient pressure gives absolute pressure;
actual volume flow rate	actual volume flow rate of gas compressed and delivered at the standard discharge point, refers to conditions of total temperature, total pressure and composition, prevailing at the standard inlet point. Also, referred as FAD (Free Air Delivery), at inlet conditions.
ambient pressure	means atmospheric pressure, expressed as absolute pressure of the atmospheric air at the air inlet of the compressor (package), before the inlet filter;
ATEX	ATmosphères EXplosibles
CEN	European Committee for Standardization
compressed volume flow rate	volume flow rate of gas at the discharge referred to conditions of total temperature, total pressure and composition, prevailing at the discharge point. This is generally not used.
D-value	proportional change in the loss of the compressor, where loss is defined as the difference between the average isentropic efficiency and the theoretical 100% efficiency
discharge pressure	total mean absolute pressure at the standard discharge point
DG ENER	Directorate-General Energy, of the European Commission
DoE	US Department of Energy
EN	European Norm
EPBD	Energy Performance of Buildings (directive)
gauge pressure	pressure measured above the atmospheric pressure. Absolute pressure minus ambient pressure gives gauge pressure;
GDP	Gross Domestic Product (economic indicator)
GWh	Giga Watt hour 10^9 Wh
HPLV	high pressure low volume flow fans (to be defined on the basis of pressure ratio (less than 1.1) and specific speed)
inlet pressure	total mean absolute pressure at the standard inlet point
isentropic efficiency	the ratio of the required isentropic power to package input power
ISO	International Standardisation Organisation
kW	kilo Watt, 10^3 W
N	rotational frequency (shaft speed), s−1 min−1
NGO	Non-Governmental organisation
normal volume flow rate	volume flow rate of compressed gas as delivered at the discharge point but referred to NTP condition of total pressure, total temperature and composition (1 bar, 0 ºC).
p	pressure, Pa, MPa (bara, mbar)
P	power, W, MW, kW
Pa	Pascal (unit of pressure)
PDP	Pressure Dew Point
ppm	parts per million
pressure ratio or compression ratio	the ratio of absolute discharge pressure to absolute inlet pressure.

P_{spec}	Specific power requirement
q	Rate of flow, kg/s or m^3/s kg/h or m^3/h, m^3/min, L/s
q_m	Mass rate of flow, kg/s kg/h
q_V	Volume rate of flow, m^3/s, m^3/h, m^3/min, L/s
R	Gas constant J/(kg·K)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (Regulation)
RoHS	Restriction of Hazardous Substances (directive)
rpm	rotations per minute
standard volume flow rate	volume flow rate of compressed gas as delivered at the discharge point but referred to standard inlet condition of total pressure, total temperature, and composition (1 bar, 20°C, R.H. 36 per cent)
t	temperature in degree Celsius, °C
T	thermodynamic temperature in degree Kelvin, K
TC	Technical Committee (in ISO, CEN, etc.)
TWh	Tera Watt hour = 10^{12} Wh
V	Volume m^3, L
VSD	Variable Speed Drive, an electric motor controller capable of continuously adapting the rotational speed of the motor, in relation to certain sensor inputs or other settings
W	Work, in J, MJ, kJ, kWh
WEEE	Waste of electrical and electronic equipment (directive)
WG	Working Group (of a TC of standardisation organisations)
yr	year (also 'a' for annum)

Figure 1 Relationship between absolute, atmospheric and gauge pressure



Conversions

1 l/s = 3.6 m^3/h = 2.19 ft^3/min (cubic feet per minute)
1 bar = 100 000 Pa = 14.504 psi (pound-force per square inch)
1 kW = 1.34 hp (horsepower)
Normal reference atmospheric pressure = 1.01325 bar = 101325 Pa = 1013.25 hPa

Preface

Background

The first DG ENER LOT 31 preparatory study for compressors started in March 2012 and was finalised June 2014. In this study 'standard air', 'low pressure' and 'oil free' were identified as application ranges possibly eligible for regulatory measures.

The energy efficiency and cost-effective saving potential of compressor packages for the 'standard air' application range was assessed in great detail in this first study, but an assessment for the low pressure and oil-free application range could not be performed due to lack of resources for this study and lack of relevant data. Rough estimates suggested some extra 4 TWh/a savings by 2030 (see Lot 31 Final Report of June 2014, Task 8, section 3.5).

The aim of the present, second, Lot 31 study is to provide a detailed assessment of possible energy savings, or other environmental improvements, for compressor packages in the low pressure and oil-free application range, taking into account effects on costs and impacts on industry.

The key affected stakeholders in this study are compressor package manufacturers active in the low pressure and oil free application ranges (represented by industry association PNEUROP, member of ORGALIME), their customers and interest groups (such as environmental NGOs).

General approach and methodology

This study is performed according the MEErP methodology, as published in 2011 and amended in 2013. The following tasks are part of the methodology:

- Task 1 Scope (product definitions, standards, legislation)
- Task 2 Markets (sales, life & stock, prices and market actors)
- Task 3 Users (use categories, operating hours, trends in controls)
- Task 4 Technologies (performances, average, BAT, BNAT)
- Task 5 Environment & economics (Ecoreport and LCC)
- Task 6 Design options (identification, costs & merits of options)
- Task 7 Policy options (policy options, scenarios)

Data collection by industries

An essential part of the information presented in Task 2 (Markets), Task 3 (Users), Task 4 (Technologies) and Task 6 (Design options), could not be retrieved without the help of the relevant industries.

An internal data collection effort by these EU industries produced information on average sales, performance, operating hours, load factor and product life of products placed on the EU market which was shared with the study authors. The authors thank the relevant industries for supplying this data.

Furthermore, together with the industries a proposal was made for identifying base cases on the basis of the volume flow control range. This approach respects the technology neutrality which is the guiding principle in ecodesign studies.

TASK 1: Scope

1 Scope

In this Task 1 the energy related products to be covered by this study are described and defined. Performance parameters are identified and (test) standards that allow assessment of these performance parameters are described.

Relevant legislation and related initiatives inside and outside the EU are outlined.

1.1 Definition of scope and categorisation

1.1.1 Initial scope of study

The terms of reference of this study require an assessment for "low pressure" and "oil-free" compressor packages, as described in the first Lot 31 study.

The terms are to be understood as follows:

- A 'compressor package' means – for the purpose of this study - a compressor comprising the compression element ('air end')[1], prime mover (electric motor) and transmission. It is fully piped and wired internally, and includes ancillary and auxiliary items of equipment required for safe, continuous and reliable operation.

  Further on in this report, in Task 4, the concept of a 'basic package'[2] is introduced, to level the playing field when comparing the performance (including efficiency) of products that offer similar functionality (or lack thereof). The 'basic package' defines the components needed for safe, continuous and reliable operation, as agreed among experts.

  Some compressors may be placed on the market in a configuration resembling the definition of a 'basic package', other compressors may have other, additional items of equipment on board, for instance for drying, and these compressors may be referred to as 'full feature' packages.

  Components that are part of the compressed air system, such as receivers, downstream compressed air filters, and terminal equipment are not considered part of the package.

- An 'application range' is a generic description of typical applications of compressors, possibly defined by performance parameters such as discharge pressure, type of gas, (risk of) presence of oil, etc.

- In the first Lot 31 study, the 'Low pressure' application range was defined as compressors with an absolute discharge pressure of approximately 1.1 to 5 bar(a) [3] but it added that exact limits are not defined.

  The bottom limit of 1.1 bar(a) for the low pressure range is aligned with the definition of a fan (upper limit) in Regulation 327/2012[4] wich was based on the definition of a compressor according ISO /TR 12942:2011 referring to a pressure ratio above 1.1,

---

[1] Where subsequent Tasks and Sections refer to a 'compressor' this is to be understood to be the compressor package. If only the 'compression element' is meant, it shall be referred to as 'compression element' or 'air end'.

[2] The concept of a basic package was introduced in the first Lot 31 study and accepted as approach for dealing with the real-world variety of compressor packages and the need for fair performance assessment.

[3] This is based on page 18 of Task 1, first Lot 31 study (Final report Lot 31 Task 1-5, 3 June 2014). On page 37 of Task 1 also a minimum pressure increase range of 50 mbar to 3.5 bar(g) is mentioned as bottom limit but this does not align with the definition of a 'compressor' which refers to a pressure ratio (outlet vs. inlet pressure) of 1.1, which means that at 1 bar(a) inlet pressure, outlet pressure must be at least 1.1 bar(a).

[4] In ISO/TR 12942:2011 the compressor is defined as "a machine or apparatus converting different types of energy into the potential energy of gas pressure for displacement and compression of gaseous media to any higher pressure values above atmospheric pressure with a pressure ratio exceeding 1.1".

assuming 1 bar(a) as atmospheric pressure. In table 6 of the first Lot 31 study a bottom limit of 50 mbar is also stated, but such pressure increase is too small to allow a minimum pressure ratio of 1.1 which is used to separate compressors from fans.

The upper limit for 'low pressure' was defined in the first Lot 31 study as 5 bar(a).

A maximum volume flow of 15 000m^3/h (4167 l/s) was proposed, which (depending on pressure ratio) coincides with a power requirement of (less than) 1 MW [5].

- The 'oil free' application range covers roughly the same range in discharge pressure as 'standard air': discharge pressure between 5-15 bar(a)[6], the bottom limit was aligned with the low pressure range.

  The maximum volume flow is proposed to be some 12 000m^3/h (3333 l/s) at 7 bar(g) = 8 bar(a), which, depending on pressure, coincides with a power requirement of (less than) 1 MW [7].

  In this study 'oil-free' is defined as "no oil inserted in the compression chamber". Insertion of water is considered to belong to "oil-free".

  In a wider, system context, standard air (which is lubricated) and oil-free air may be competing for the same business opportunities. However, a comparison of standard air versus oil-free requires consideration of a much wider system than just the product (package) boundaries, taking into account the application and use of filters, dryers and other system aspects.

1.1.2 Outside scope of study

Similar to the first Lot 31 study, this additional study does not look into:

- Refrigeration compressors;

  Already in the preceding Lot 31 study on standard air it was argued that refrigeration compressors (including heat pump applications etc.) should be kept outside the scope of the study because of quite different technical requirements (refrigeration is a closed system, whereas air compressors allow venting) and stakeholders agreed (see also Minutes of the Consultation Forum 23 Oct 2014 on standard air).

- Compressors used in 'process' applications:

  These are compressors handling gases other than standard air (including hazardous gases or flammable gases) and/or at pressure levels beyond 15 bar(a) and/or operate beyond the boundaries described above[8];

- Vacuum 'pumps';

  Certain compressor technologies can be applied as vacuum pump. But a vacuum is not compressed air, and vacuum technology is much, much wider than using vacuum pumps with operating principles similar to compressors. Therefore vacuum applications are outside the scope of the study.

- Means of transport

  The Ecodesign and Energy labelling Directive exclude 'means of transport' from their scope (art. 1.3 of 2009/125/EC and 2010/30/EC) but this term is not further defined. Some guidance is provided in the FAQ document[9] by the European Commission which

[5] Source: PNEUROP JWG Communication, 16 March 2016

[6] The data collection as performed for Task 4 covered oil-free equipment in the range of 5 to 15 bar(a). The survey did show that sales in the 5-7 bar(a) range are very small compared to other pressure ranges.

[7] Source: PNEUROP JWG Communication, 16 March 2016

[8] The boundaries for volume flow rate will be assessed after finalization of Task 2 and other relevant tasks.

[9] Frequently asked questions on the Energy Labelling Directive and its implementing Regulations, last updated November 201 5 (not legally binding).

states (on p. 5) *"products that are specifically constructed only for application in means of transport (including mobile homes and caravans) and no other applications, are exempted from energy labelling regulations"*. Although this elaboration is limited to Labelling only and bears no legal power, it does indicate that products to be used in means of transport are to be excluded from the Directives (assuming that the interpretation is the same for the Ecodesign Directive) and can be excluded from the scope of this study

- Compressors not driven by electric motors

  The scope of the study is limited to compressor packages driven by electric motors. This excludes compressors driven by gas turbines, steam or other types of drivers. The limitation to electric motor driven products can be traced back to Article 16.2.a of Directive 2009/125/EC which mentions the Working Plan covering "electric motor systems" as "products which have been identified by the ECCP as offering a high potential for cost-effective reduction of greenhouse gas emissions". The Directive 2010/30/EU on energy labelling refers to this Working Plan in recital (7). Compressors are one of multiple groups of products covered by 'electric motor systems' (other product groups are: electric motors and their drives (Lot 30), pumps (Lot 28, 29), fans (Lot 11).

Type of motor

The former Lot 31 study established that the majority of compressors used three-phase electric motors. For this reason, the scope proposed in the 2014 Working Document on standard air compressor packages was limited to three-phase motors.

In practice single phase motors are mostly applied up to approximately 0.75 kW output power[10]. The group of 'Medium' motors runs from 0.75 kW to 375 kW and covers mostly three-phase motors plus some other technologies (such as permanent magnet, switched reluctance, etc.). Single phase motors above 0.75 kW do exist but the Lot 30 motor study states that *"[these motors] will not be considered because of their relatively lower performance compared with 3-phase motors and because of their declining market share"*[11].

For this reason it will be assumed in this study that compressor packages with input powers above 0.75 kW, or driven by electric motors with a rating exceeding 0.75 kW are primarily three-phase and are covered by this study.

Table 1 Scope of low pressure and oil-free application range according first Lot 31 study

	Outlet pressure range (bar(a))	**Volume flow range (l/s)** [12]	**Technologies**
Low pressure	1.1 < $p_2 \leq$ 5 bar (a)	< 15 000 m³/h	Roots, side channel, liquid ring, claw, dry vane, screw, turbo and multistage turbo
Oil-free	7 $\leq p_2 \leq$ 15 bar(a)	< 12 000 m³/h @ 7 bar(e)	Piston, scroll, water-injected screw, rotary tooth 2-stage, screw 2-stage, Integrally geared 2/3-stage turbo

In general each compressor package can be operated over a pressure band, e.g. from 3 to 8 bar(a). If this band crosses the threshold pressure between low pressure and oil-free, it should be avoided that this equipment is then covered by two different measures (if any). Therefore a reference point should be identified to rate and classify the product. An example of such a reference point is given in Task 4 (see references to 'point 4' in the operating range).

[10] See final report of Lot 30, April 2014, Task 1, p. 5, "small motors in the power range of 120 W to 750 W"

[11] See final report of Lot 30, April 2014, Task 1, p. 6. However, in the subsequent Task reports single phase motors are still covered and in Task 7 a minimum IE2 is recommended (no indication of power given).

[12] PNEUROP presentation 16-3-2016

1.1.3 Categories according EN- or ISO standards

Categorisation of compressors is dealt with in ISO TR 12492 (not an 'official' standard, but a technical report TR) which is complementary to the much older ISO 5390:1977. The Technical Report was intended to contribute to a possible revision of ISO 5390. ISO/TR 12942 was prepared by Technical Committee ISO/TC 118, Compressors and pneumatic tools, machines and equipment, Subcommittee SC 6, Air compressors and compressed air systems.

ISO/TR 12942 (Technical report) presents a classification of compressors based on design classes (classification by type, operation principles) and functional classes (basic functional classes, derivative functional classes) and service-duty classification (Annex A of ISO/TR 12942:2012).

Categorisation of compressor machines can be on the basis of the operation principle. Essentially there are two ways to increase the pressure of a gas: Either by "positive displacement", or by a "dynamic" transfer of energy between a moving rotor and the fluid, also known as "turbo compressors". The ISO/TR 12942 definitions are provided below:

1. **Positive-displacement compressor**: a compressor machine in which the admission and compression of successive volumes of the gaseous medium are performed periodically by forced expansion and diminution of a closed space(s) in a working chambers(s) by means of displacement of a moving member(s) or by displacement and forced discharge of the gaseous medium into the high-pressure area.

   NOTE The closed spaces with variable or displaceable volumes represent compression chambers. In one working chamber, there can be one or several variable-volume compression chambers.

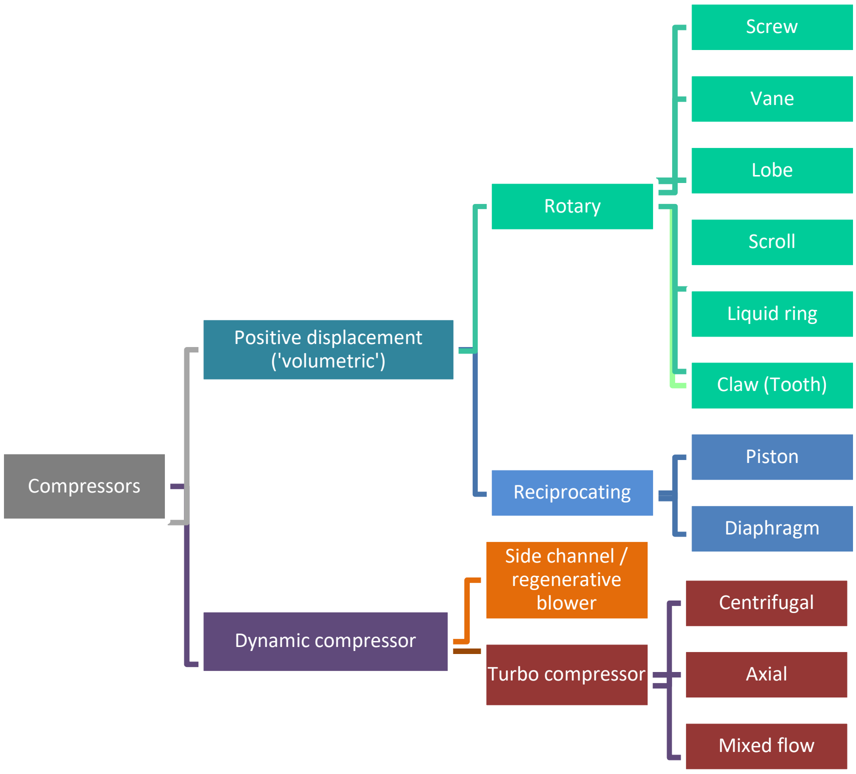
2. **Dynamic compressor ('turbo compressors & side channel blowers')**: a compressor machine in which the gas pressure increase is achieved in continuous flow essentially by increasing its kinetic energy in the flow path of the machine due to acceleration to the high velocities by mechanical action of blades placed on a rapid rotating wheel and further transformation of the kinetic energy into the potential energy of the elevated pressure by successive deceleration of the said flow.

A third option is the combined use of displacement and dynamic action, the 'combined compressor machine':

3. **Combined compressor machine**: a compressor machine in which the compression of gaseous medium or media is performed simultaneously or successively by dynamic and positive-displacement compressors driven by a common prime mover.

Within these main groups, positive displacement and dynamic, there is a wide variety of working principles. The figure below gives an overview of the main working principles (non-exhaustive).

Figure 2 Categorisation of compressors, by working principle



ISO/TR 12942 provides compressor categorisation and classification based on many approaches, many of which may be related to an application range of which a wide spectrum and diversity exists. This results in a great number of applicability and performance criteria, such as:

- compression principles;
- basic design features;
- media;
- energy forms used (electricity, fuel heat, etc.) and driver types;
- cooling agents (air, water, etc.) and methods;
- lubrication conditions (oil-free or oil-injected, oil-lubricated);
- mobility, transportability;
- prefabrication level (packaged and factory-assembled compressor, compressor plant, etc.);
- operation modes and service parameters;
- range of functions (compression, energy conversion, cooling, drying, etc.) and appropriate structural composition of the equipment.

The classification according ISO/TR 12942 is primarily driven by technical features and parameters, and not by application.

Low pressure as service pressure class in ISO/TR 12942

In ISO/TR 12942[13] service pressure classes (section 4.5.3) for discharge pressure are defined:

[13] ISO/TR 12942:2011(E)

- Ultra-low-pressure compressor plants: A compressor plant for absolute discharge pressures up to 2 bar[14].
- Low-pressure compressor plants: A compressor plant for absolute discharge pressures in the range of 2 bar to 15 bar;
- Medium-pressure compressor plants: A compressor plant for absolute discharge pressures in the range of 16 bar to 101 bar;
- High-pressure compressor plant: A compressor plant for absolute discharge pressures in the range of 101 bar to 1 001 bar;
- Ultra-high-pressure compressor plants (Hyper compressor plants): A compressor plant for absolute discharge pressures exceeding 1 001 bar.
- Two-discharge pressure compressor plants: A compressor plant with inter-stage gas take-off under the intermediate gas pressure.
- Pumping-up compressor plants: A compressor plant operating cyclically with constant suction and variable, periodically increasing discharge pressure[15]

In addition to this ISO/TR 12942 defines in section 4.5.3 on Combined-service and relative pressure classes a 'Blower plant' which is 'a compressor plant with discharge-/suction-pressure increase ratios not exceeding 2,0 regardless of the absolute pressure level'.

From the above it is clear that the ISO/TR 12942 definition of low pressure does not align with the discharge pressures of the intended application range.

Oil-free as design class in ISO/TR 12942

Oil-free however is defined in ISO/TR 12942 as follows:

In section 2.5.2.3 Design classes of double-rotor compressors of ISO/TR 12942 'Oil-free screw compressor timing gear intermeshing screw compressor' are defined as 'an externally meshing double-rotor compressor in which the rotors have helical lobes and grooves, volumes of said grooves being cyclically decreased and increased by engagement and disengagement of each groove-lobe pair, and their simultaneous shifting from low pressure rotor end to the high-pressure end due to their synchronized rotation'.

In section 4.5.2 Lubrication classes an 'Oil-free compressor plant' is defined as 'A compressor plant with a displacement compressor operating without injection of lubricating liquid into the working chambers in which the compressed gas does not come into contact with any lubricant thanks to their rubbing parts being made of self-lubricating materials, or working members moving without contact with each other or with working chamber surfaces. An Oil-free compressor plant does not need any oil-separation equipment.

These technical descriptions are adequate for defining oil-free working principles, but do not set boundaries or limits in terms of discharge pressure (or pressure ratio) and volume flow rates, which is also required when defining an application range.

It is therefore concluded that the application ranges (the combination of technical descriptions and primary/secondary parameters) are not defined in international standards.

In the LPWG Guideline for verifying the performance of low pressure compressors, low pressure is defined by limits for inlet pressure, pressure increase and/or pressure ratio.

- 0,5 bar <= p1 <= 1,5 bar
- 0,1 bar <= Δp <= 3,5 bar
- p2 /p1 <= 4,5

What this means for the maximum outlet pressure at varying inlet pressures is shown in the table below.

[14] 1 bar = 0,1 MPa = 10^5 Pa; 1 MPa = 1 N/mm2

[15] The pumping-up compressors can be used for filling high-pressure gas cylinders

Table 2 LPWG definition of Low Pressure

Inlet pressure p1	Max. discharge pressure p2	
	Pressure difference	Pressure ratio
	Δp <= 3,5 bar	p2 /p1 <= 4,5
0.5 bar(a)	4 bar(a)	2.25 bar(a)
1 bar(a)	4.5 bar(a)	4.5 bar(a)
1.5 bar(a)	5 bar(a)	6.75 bar(a)[16]

1.1.4 Categorisation according Prodcom

Prodcom provides statistics on the production and trade of manufactured goods in the EU[17]. The following codes are related to compressors.

Table 3 Prodcom codes related to "compressors"

Code	Description
28132300	Compressors for refrigeration equipment
28132400	Air compressors mounted on a wheeled chassis for towing
28132530	Turbo-compressors, single stage
28132550	Turbo-compressors, multistage
28132630	Reciprocating displacement compressors having a gauge pressure capacity ≤ 15 bar, giving a flow ≤ 60 m³/hour
28132650	Reciprocating displacement compressors having a gauge pressure capacity ≤ 15 bar, giving a flow per hour > 60 m³
28132670	Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour ≤ 120 m³
28132690	Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour > 120 m³
28132730	Rotary displacement compressors, single-shaft
28132753	Multi-shaft screw compressors
28132755	Multi-shaft compressors (excluding screw compressors)

It can be concluded that there are no specific Prodcom categories for compressors in specifically the low pressure or oil-free application ranges.

1.1.5 Categories according Energy- and/or Eco-labels in the EU

There are currently no EU energy or Ecolabels for industrial compressors for air or other gases.

1.2 Test standards

This section describes relevant test standards for:

[16] Assuming an inlet pressure of 1.5(a) and a pressure ratio of 4.5, the outlet pressure is 6.75 bar(a): 1.5 * 4.5 = 6.75

[17] http://ec.europa.eu/eurostat/web/prodcom

- primary and secondary functional performance parameters (section 1.2.1 and 1.2.2);
- resources use and emissions during product-life (section 4.8);
- safety (gas, oil, electricity, EMC, stability of the product, etc.) (section1.3);

These standards can be:

- harmonised measurement standards (see section 1.2.10);
- sector-specific standards or directions for product measurement.

Standards applicable in Member States and in third countries are covered in section 1.2.6 and 1.2.7 respectively.

1.2.1 Primary performance parameters

The primary performance parameters are:

1) Discharge pressure (bar(a)) or pressure increase (bar(g)) or pressure ratio (p2/p1);
2) Volume flow rate (l/s, or m^3/hr);
3) Power input (e.g. in kW);
4) Isentropic efficiency (%), "energy efficiency".

Pressure and volume flow rate (and the isentropic efficiency derived from those) have to be linked to standard inlet conditions to allow comparative assessments.

Standard inlet conditions

Ideally tests are carried out in conditions identical to the end application. In reality such conditions cannot always be reproduced in test labs. Therefore performances are established using real inlet conditions and then recalculated to performances at standard inlet conditions (as common for ISO 1217) or agreed conditions (common for ISO 5389).

In ISO 1217:2009, Annex F, for positive displacement compressors, the 'standard inlet conditions' are:

- Inlet air pressure 100 kPa [1 bar] (a);
- Inlet air temperature 20 °C;
- Relative water vapour pressure 0 (zero);
- Cooling water temperature 20 °C.

ISO 5389:2005 for turbo compressors describes various methods to convert test values to guaranteed values. Standard inlet conditions may be considered as a special set of guaranteed values. In (informative) Annex E.4 (standard volume flow) a standard volume flow is defined at pressure 101.325kPa and 0ºC. Humidity is taken into account in the equation for calculating mass flow and not prescribed.

The LPWG Guidelines defines as standard reference conditions an inlet pressure of 101.325 kPa a temperature of 20ºC, zero moisture and 20ºC coolant temperature.

In many instances performance is stated as FAD (Free Air Delivery). This term is neither defined in ISO 1217 or ISO 5389. FAD is normally defined as "delivered flow converted back to the inlet thermodynamic condition". If the inlet conditions are equal to ISO 1217 conditions then (as in this paragraph) q_{FAD} is referred to the standard condition. Otherwise FAD is referred to the suction condition. It therefore may depend on the manufacturer/supplier what is actually meant by FAD.

Air delivery or volume flow rate is preferably expressed in the SI units m^3/s. However, m^3/h or l/s is also frequently used (not to mention imperial units such as cfm, cubic feet per minute). In most cases FAD recalculation is done for an inlet pressure of 1 bar and inlet temperature 20ºC. This corresponds to the standard inlet conditions as specified in ISO 1217, Annex F.

Sometimes the volume flow rate is stated as Normal litre/second (Nl/s) which should relate to inlet conditions of 1.013 bar(a) and 0ºC. The Normal unit Nl/s is primarily used when specifying a mass flow.

Ignoring humidity the Normal unit can be converted to free air according to:

Equation 1 Free air delivery

$$q_{FAD} = q_N * \frac{T_{FAD}}{T_N} * \frac{P_N}{P_{FAD}} = 1.08 q_N$$

or $q_N = 0.92 * q_{FAD}$

With
q_{FAD} = free air delivery (l/s) at ISO 1217 standard inlet conditions
q_N = Normal volume rate of flow (Nl/s)
T_{FAD} = standard inlet temperature (20ºC = 273 + 20 K)
T_N = Normal reference temperature (0ºC = 273 K)
P_{FAD} = standard inlet pressure (1.00 bar(a))
p_N = Normal reference pressure (1.013 bar(a))
Note: the equation only applies when inlet conditions are as ISO 1217.

Using correct and unambiguous terms and units is important. As an example, in many cases manufacturers state pressure as 'p_e' which refers to 'effective pressure' instead of the more appropriate 'gauge pressure'[18] or 'absolute pressure'.

The table below shows the various standard inlet conditions described, and includes the inlet conditions that have been used in the performance survey in this present study.

Table 4 Overview of standard inlet conditions

Source	p_1	T_1	H_2O	coolant
ISO 1217, Annex F	100 kPa	20ºC	0 %	20ºC
ISO 5389, Annex E	101.325 kPa	0ºC	(to be indicated)	(not indicated)
LPWG	101.325 kPa	20ºC	0 %	20ºC
Lot 31 data collection	100 kPA	20ºC	0 %	20ºC
	Only for oil-free: dT (outlet - inlet) < 25 K			

Isentropic efficiency

Energy efficiency in this document is defined as the work of an isentropic reference process related to electric input work. In this study the electric input work will be the electric input power of the package.

Equation 2 Isentropic (energy) efficiency

$$\eta_s = \frac{P_s}{P_e}$$

Where:
η_s = isentropic efficiency
P_s = isentropic power
P_e = electric input power of package

[18] "p_e" is an expression which is originally related to calculations of strength of vessels and like products, and describes the difference between internal and external pressure because this difference creates the forces acting on the vessel.

The reference process (isentropic power) is the numerator in the equation for calculating efficiency of a compressor (with input power as denominator). The isentropic process assumes no heat exchange with the environment (temperature rises).

Equation 3 Isentropic power, in accordance with ISO 1217-A1-2016 (new Annex H)

$$P_{isen} = q_{V1} \cdot p_1 \frac{\kappa}{(\kappa - 1)} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]$$

Where:

q_{V1} is the volume flow rate (m^3/s);
p_1 is the pressure at the inlet (Pa);
p_2 is the pressure at the discharge (Pa);
κ is the isentropic exponent (ratio of specific heats) (-);

Isentropic power can also be calculated using a simplified equation (no SI units), assuming dry air as medium, 1 bar inlet condition, and the flow in l/s and pressures in bar(a).

Equation 4 Simplified calculation of isentropic power

Pisen = 0.35 * flow* (p2^0.287 -1)

Where:
flow = volume flow rate, in l/s
p2 = outlet pressure, in bar(a)

The electric input power is to be measured at the power terminal of the (basic) package.

1.2.2 Secondary performance parameters

Secondary performance parameters describe other aspects relevant for the operation or functioning of the equipment, or its end-use, such as:

1) Discharge air quality (ISO 8573);
2) Control capabilities in relation to application:
    a) constant or variable volume flow;
    b) constant or variable discharge pressure;
    c) output in relation to changes in input (temperature of inlet air, inlet pressure);
3) Heat rejection (air- and/or water cooled);
4) Heat recovery;
5) Sound emission;
6) Servicing / reliability / risk of malfunction / risk & costs of downtime;
7) Dimensions (L*W*H) and weight, in particular for compressors integrated into other machinery.

The type of gas handled by the equipment is essentially also a secondary performance parameter, but as this study considers equipment for compressed air only it shall be ignored in the remainder of the study.

1.2.3 Performance standards

Standards to be used for assessment of primary and secondary performance parameters are:

Table 5 Standards for primary and secondary performance parameters

Performance parameter	Positive displacement compressors	Dynamic compressors
Primary		
– **volume flow rate**	ISO 1217	ISO 5389 including ISO/FDIS 18740 (fixed speed)
– **discharge pressure**	ISO 1217	ISO 5389 including ISO/FDIS 18740
– **Isentropic efficiency**	ISO 1217:2009 / Amd.1:2016 (E)	ISO 5389:2005, Formula (E.101)
– **Power input**	ISO 1217	ISO 5389 including ISO/FDIS 18740 (fixed speed)
Secondary		
– **Discharge air quality**	ISO 8573	
– **Sound emission**	ISO 2151:2004	
– **Control capabilities in relation to application**	To be verified on the basis of definitions for these control capabilities	
– **constant or variable volume flow**		
– **constant or variable discharge pressure**		
– **output in relation to changes in input (temperature of inlet air, inlet pressure);**		
– **Cooling (heat rejection, air- or water cooled)**	To be verified on the basis of manufacturer information	
– **Heat recovery**	No standards exist to measure heat recovery performance	
– **Servicing / reliability / risk of malfunction / risk & costs of downtime**	API 619 (5th ed. 2010) describes a minimum service life and a minimum for uninterrupted performance. It does not state how it shall be tested or verified as it is a design criterion.	
– **Dimensions (L*W*H) and weight**	To be verified on the basis of manufacturer information	

Regarding performance assessment of compressor packages (neither low pressure and oil-free, or standard air) no relevant EU legislation yet exist and mandates for the development of such standards have not yet been issued by the European Commission (status: July 2016).

ISO 1217: 2009, **Displacement compressors - Acceptance tests**

The "Displacement compressor" covered by ISO 1217 is defined in this standard as:

- **Displacement compressor**: a machine that creates a static pressure rise by allowing successive volumes of gas to be aspirated into and exhausted out of a closed space by means of the displacement of a moving member

The standard also describes the following subtypes of compressors (a.o.):

- **Packaged compressor**: a compressor with prime mover, transmission, fully piped and wired internally, including ancillary and auxiliary items of equipment and being stationary or mobile (portable unit) where these are within the scope of supply;
- **Packaged compressor power input** ⟨electrically driven machines⟩ sum of the electrical power inputs to the prime mover and any ancillaries and auxiliaries driven from the compressor shaft or by a separate prime mover at rated supply conditions, including the effect of all equipment included in the package

  NOTE 1 Auxiliaries include oil pump, cooling fan and integral compressed air dryer.
  NOTE 2 Rated supply conditions refer to phase, voltage, frequency and ampere capability.
- **Shaft power:** power required at the compressor drive-shaft, equal to the sum of mechanical losses and the internal power, not including losses in external transmissions such as gear drives or belt drives unless part of the scope of supply

This International Standard specifies methods for acceptance tests regarding volume rate of flow and power requirements of displacement compressors. It also specifies methods for testing liquid-ring type compressors.

This International Standard specifies the operating and testing conditions which apply when a full performance test is specified.

Annex E, which is normative, applies to any electrically driven compressor manufactured in batches or in continuous production quantities and supplied against specified data, having variable speed drive (e.g. variable frequency drive, direct current drive and switched reluctance), which incorporates a displacement compressor of any type driven by an electric motor.

Detailed instructions are given for a full performance test, including the measurement of volume flow rate and power requirement, the correction of measured values to specified conditions and means of comparing the corrected values with the guarantee conditions.

Annex H describing the calculation of isentropic efficiency is now also available as ISO 1217:2009/Amd.1:2016(EN) "Displacement compressors — Acceptance tests AMENDMENT 1: Calculation of isentropic efficiency and relationship with specific energy"[19].

CEN/TC 232 is working to introduce in ISO 1217 concepts that have been introduced in the EU Working Document on 'standard air' compressor packages, such as the 'Cycle energy requirement' (assessing transient energy losses) into the relevant ISO standards. So far, this work has not been concluded.

ISO 5389: 2006 Turbo compressors - Performance test code

The "Turbo compressors" is defined in ISO 5389 as: "machines in which inlet, compression and discharge are continuous flow processes. The gas is conveyed and compressed in impellers and decelerated with further increase in pressure in fixed vane or vane less stators".

Performance test code ISO 5389 excludes (high) vacuum pumps and jet-type compressors from its scope. Recently standardisation work is completed that added a simplified acceptance test code for (fixed speed) turbo compressors as annex to ISO 5389. There is currently no initiative other than the periodic review of the standard.

The ASME PTC 10: Industry standard for performance measurement of turbo compressors is similar to ISO 5389 and applies to performance tests on turbo compressors of all types. It does not apply to fans and high-vacuum pump or to jet-type compressors with moving drive components. ASME is also working on PTC 13 for all types of low pressure compressors.

[19] https://www.iso.org/obp/ui#iso:std:iso:1217:ed-4:v1:amd:1:v1:en

ISO 18740 Performance turbo compressors / simplified test -

ISO 18740[20] describes a 'Simplified acceptance test' for fixed speed Turbo compressors, and was published July 2016. The text below from the ISO website[21] introduces the standard and the scope.

Introduction

ISO 5389 is the primary standard for performance statements of dynamic compressors of all types. For electrically driven packaged air compressors of standard types which are constructed to specifications determined by the manufacturer and which are sold against performance data published in the manufacturer's sales documentation ISO 5389 provides for demanding conditions to be met for such standard packages.

To allow performance statements to be made for standard types this simplified code has been developed where the performance statement can be given based on specified test conditions where the key measured variables are maintained within identified test limitations.

The performance statement is valid provided it is within the identified acceptance allowances for volume flow rate, specific power consumption and unloaded power consumption.

Whereas ISO 5389 address any type of dynamic compressor this simplified standard addresses centrifugal compressors only which are of the fixed speed type. It is envisaged that at a later date variable speed types will also be included.

This standard will ultimately become an annex of ISO 5389 once sufficient experience has been gained from its use in the field. In its current form it complements ISO 5389 for standard packages but where acceptance tests are required to demonstrate fulfilment of the order conditions and guarantees specified in the contract then ISO 5389 is still the primary reference standard.

Scope

This International Standard applies to any fixed (constant) speed, liquid cooled, packaged centrifugal air compressor which incorporates a centrifugal compression element of any type driven by an electric motor.

This International Standard defines and describes acceptance tests for electrically driven packaged air compressors of standard types which are constructed to specifications determined by the manufacturer and which are sold against performance data published in the manufacturer's sales documentation.

Such packaged compressors are usually fully piped and wired and generally include all ancillary items necessary for their effective operation as a complete self-contained air compressor installation.

Those items included in the test shall be indicated from the listing given in Clause 7 [22].

NOTE Items supplied shipped loose for installation at site are not considered to be a part of the compressor package.

Such compressors are designed to draw in atmospheric air from their immediate surroundings and the performance data offered by the manufacturer usually relates to a normal ambient air inlet pressure.

ISO 8573 Compressed air quality

ISO 8573 defines classes of air quality and identifies the appropriate standards or methods to be applied to measure air quality.

[20] https://www.iso.org/obp/ui#iso:std:iso:18740:dis:ed-1:v1:en and http://www.iso.org/iso/catalogue_detail.htm?csnumber=63235

[21] https://www.iso.org/obp/ui#iso:std:iso:18740:dis:ed-1:v1:en

[22] *see actual standard for text*

This standard is therefore required for establishing the class of air quality (particle content, oil content, water content) secondary performance parameter.

1991 ISO 8573-1

The 1991 ISO 8573-1 edition of the air quality standard established five purity classes, 1 through 5. The best, Class 1, specified an oil concentration of ≤ 0.01 mg/m^3 at 1 bar(a) and 20°C. Conformance to Class 1 was sometimes called “a technically oil-free solution”.

However, only oil aerosols and liquids were considered. Below 35°C, vapours could be ignored when, in fact, the quantity of vapours may be higher than aerosols.

2001 ISO 8573-1

In 2001, the standard was revised to address the needs of applications where air purity is essential.

These include industries such as pharmaceuticals, food and beverages, electronics, automotive painting and textiles.

The 2001 revision established a more comprehensive outlook by specifying the measurement of total oil content, as opposed to the earlier edition which called for the measurement of aerosols and liquids alone and not the vapours, below 35°C. Moreover, to the existing purity classes 1 through 5, a new and more stringent class was added: ISO 8573-1 "Class 0". Class 0 is not defined by limits as class 1-5, but by limits "more stringent than class 1" as specified by the "equipment user or supplier". "Class 0 certification" is mainly a marketing term as the exact limits are not defined in ISO 8573.

2010 ISO 8573-1

The evolution of the ISO8573-1 standards over time reflects the ever increasing need for quality air for process and sensitive end products like foodstuffs and pharmaceutical.

The ISO 8573-1 (2010) edition was revised to reflect a change in dust content specifications.

Oil classes

The oil purity classes dealing with liquid oil, vapour and aerosols of oil are measured in accordance with ISO 8573-2 and, when required the oil vapour content ISO 8573-5 shall be used. The defined classes can be seen in the table below.

Table 6 Compressor purity classes for total oil

Class	**Concentration of total oil[a] (liquid, aerosol and vapour) mg/m^3 at 1 bar(a) and 20°C**
0	As specified by the equipment user or supplier and more stringent than class 1
1	≤0.01
2	≤0.1
3	≤1
4	≤5
X	>5

[a] At reference conditions

The air quality required determines to a large degree which compressor types (most obviously: oil-free or lubricated) and ancillary equipment (oil separators, filters, condensers) are needed. This in turn influences overall energy consumption and efficiency.

Humidity and liquid water classes

The humidity and liquid water purity classes are measured in accordance with ISO 8573-3 and, when required with ISO 8573-9. The defined classes can be seen in the table below.

Table 7 Compressor purity classes for humidity and liquid water

Class	Pressure dew point °C
0	As specified by the equipment user or supplier and more stringent than class 1
1	≤ -70
2	≤-40
3	≤-20
4	≤3
5	≤7
6	≤10
Class	**Concentration of liquid water**[a] C_w g/m^3
7	$C_w \leq 0.5$
8	$0.5 < C_w \leq 5$
9	$5 < C_w \leq 10$
X	$C_w > 10$

[a] At reference conditions

Particle classes

The particle classes are measured in accordance with ISO 8573-4 and, when required with ISO 8573-8. The defined classes can be seen in the table below. The classification 1-5 cannot be applied for particle sizes greater than 5 µm.

Table 8 Compressed air purity classes for particles

Class[a]	Maximum number of particles per cubic metre as a function of particle size, d[b]		
	0.1 <d ≤ 0.5 µm	0.5<d≤ 1.0 µm	1.0<d≤5.0 µm
0	As specified by the equipment user or supplier and more stringent than class 1		
1	≤20 000	≤ 400	≤ 10
2	≤ 400 000	≤ 6 000	≤ 100
3	Not specified	≤ 90 000	≤ 1000
4	Not specified	Not specified	≤ 10000
5	Not specified	Not specified	≤ 100000
Class	**Mass concentration**[b] C_p mg/m^3		
6	$0 < C_p \leq 5$		
7	$5 < C_p \leq 10$		
X	$C_p > 10$		

a To qualify for a class designation, each size range and particle number within a class shall be met

b At reference conditions

API STANDARD 619/ISO 10440-1:2007 - on service life

Rotary-Type Positive Displacement Compressors for Petroleum, Petrochemical and Natural Gas Industries

The America Petroleum Institute has published several standards related to product design and performance of compressors used in the petroleum and gas industry. For rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries API has created API 619. This edition of API Standard 619 is the identical national adoption of ISO 10440-1:2007.

This standard covers the minimum requirements for dry and oil-flooded helical lobe rotary compressors used for vacuum or pressure or both in petroleum, petrochemical, and natural gas industries. It is intended for compressors that are in special-purpose applications. It does not cover general purpose air compressors, liquid ring compressors, and vane-type compressors.

API 619 covers basic design requirements and in section 5.1.1. it states that "The equipment (including auxiliaries) covered by this standard shall be designed and constructed for **a minimum service life of 20 years** and **at least 3 years of uninterrupted operation.** Note: It is recognized that this is a design criterion.

API 619 also specifies standard volume flow conditions:

- Pressure: 1.013 bar
- Temperature: 0°C
- Note: The standard volume flow is determined for dry gas
- The volume flow is to be expressed in cubic meters per hour (m^3/h), or cubic meters per minute (m^3/min).

API 619 is the basis for two other ISO standards:

- ISO 10440-1:2007 specifies requirements for dry and oil-flooded, helical-lobe rotary compressors used for vacuum or pressure or both in petroleum, petrochemical, and gas industry services. It is intended for compressors that are in special-purpose applications;

  ISO 10440-1 was prepared by Technical Committee ISO/TC 118, Compressors and pneumatic tools, machines and equipment, Subcommittee SC 1, Process compressors[23].
- ISO 10440-2:2001: Petroleum and natural gas industries—Rotary-Type Positive-Displacement Compressors Part 2—Packaged air compressors (oil free). This standard thus covers oil-free equipment for 'air' applications.

  International Standard ISO 10440-2 was prepared by Technical Committee ISO/TC 118, Compressors, pneumatic tools and pneumatic machines and Technical Committee ISO/TC 67, Materials, equipment and offshore structures for petroleum and natural gas industries, Subcommittee SC 6, Processing equipment and systems[24].

API 619 may be of interest when discussing the product life as secondary performance parameters.

ISO 2151 Noise emissions

ISO 2151:2004(en) Acoustics — Noise test code for compressors and vacuum pumps — Engineering method (Grade 2)

The noise test code presented by this International Standard describes methods for determining and presenting the acoustical characteristics of compressors and vacuum pumps, i.e. the total noise level from the compressor or vacuum pump expressed as sound power level, or the emission sound pressure level at the work station or other specified positions.

[23] https://www.iso.org/obp/ui/#iso:std:iso:10440:-1:ed-2:v1:en

[24] https://www.iso.org/obp/ui/#iso:std:iso:10440:-2:ed-1:v1:en:sec:A

Based on current industry practice, this noise test code requires the compressor or vacuum pump under test to be run under conditions representing the noisiest operation in typical usage — full-load for compressors and off-load for vacuum pumps.

It needs to be noted that operators' exposure to noise depends upon the characteristics of individual applications and environmental factors beyond the control of the manufacturers of compressors and vacuum pumps.

This International Standard does not give requirements for octave band analysis, however, where there is an interest this can be undertaken.

No standards relating to vibrations have been identified.

Heat recovery

Generally speaking each compressed air system can be rigged so that heat from the package can be recovered. However, no standards have been developed (yet) that allow unambiguous assessment of the amount of heat recovered.

1.2.4 Resource use and emissions during product life

The study methodology requires an inventory of possible standards for "resource use and emissions during life". There are currently no test standards specific for air compressors regarding resource use and emissions during life. But there are generic standards for life cycle assessment such as the ISO 14 000 series, including ISO 14044 for LCA.

Table 9 Generic standards related to resource use and emissions during life

Standard or project	Stage	ICS
ISO 14040:2006 **Environmental management—Life cycle assessment—Principles and framework**	90.60	13.020.60 13.020.10
ISO 14044:2006 **Environmental management—Life cycle assessment—Requirements and guidelines**	90.60	13.020.60 13.020.10
ISO 14045:2012 **Environmental management—Eco-efficiency assessment of product systems—Principles, requirements and guidelines**	60.60	13.020.60 13.020.10
ISO 14046:2014 **Environmental management—Water footprint—Principles, requirements and guidelines**	60.60	13.020.60 13.020.10
ISO/TR 14047:2012 **Environmental management—Life cycle assessment—Illustrative examples on how to apply ISO 14044 to impact assessment situations**	60.60	13.020.10 13.020.60
ISO/TS 14048:2002 **Environmental management—Life cycle assessment—Data documentation format**	90.93	13.020.10 13.020.60
ISO/TR 14049:2012 **Environmental management—Life cycle assessment—Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis**	60.60	13.020.10 13.020.60
ISO/TS 14071:2014 **Environmental management—Life cycle assessment—Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006**	60.60	13.020.60
ISO/TS 14072:2014 **Environmental management—Life cycle assessment—**	60.60	13.020.60

Requirements and guidelines for organizational life cycle assessment	
ISO/AWI TR 14073 **Environmental management—Water footprint—Illustrative examples on how to apply ISO 14046**	20.00

The actual data to be used for such assessments is however in most cases derived from commercially (or sometimes freely) available Life Cycle Inventory databases. Depending on which LCI and LCIA method is used, the actual impacts from resource use and emissions during these life cycles may differ.

Classification and characterisation of impacts and the range of impact categories taken into account depend on the Impact assessment methodology used.

The MEErP uses the EcoReport tool (Excel-based) which is a streamlined LCA approach.

The EPLCA[25] (European platform on life cycle assessment) is hosting a LCI database (ELCD) for key materials, energy carriers, transport, and waste management, and describes the indicators and models recommended for Life Cycle Impact Assessment.

The EC has developed the PEF (Product Environmental Footprint) methodology to further harmonise the LCA approach to be used. It centres around Product Category Rules (PCR), which are documents that describe how to perform an LCA for a specific product category. No such documents have been issued for (air) compressors.

Other standardisation documents as referenced in the request for standardisation M543[26] mentions as possible relevant documents:

- BS 8887:1. "Design for Manufacture, assembly, disassembly and end-of-life processing (MADE)". British Standards. 2006
- EN 50625-1 "WEEE General Treatment Requirements"
- CEN TS 16524 "Mechanical products - Methodology for optimizing environmental impacts in product design and development". CEN/TS 16524. 2013.
- EN 15343. Plastics. Recycled plastics. Plastics recycling traceability and assessment of conformity and recycled content. 2007;
- EN 15804 "Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products". This standard for building products, which refers to recycling and resource efficiency aspects.
- IEC/TR 62635 "Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment". International Electro technical Commission (IEC). Edition 01 (2012-10-19).
- IEC 62309 Dependability of products containing reused parts - Requirements for functionality and test. International Electro technical Commission (IEC). 2004.
- IEC, 60312-1. Vacuum cleaners for household use – Part 1: dry vacuum cleaners – Methods for measuring the performance (September 2010).
- IEEE 1680.1, 2009 IEEE Std 1680.1™-2009. IEEE Standard for Environmental Assessment of Personal Computer Products, Including Notebook Personal Computers, Desktop Personal Computers, and Personal Computer Displays. The Institute of Electrical and Electronics Engineers.

[25] http://eplca.jrc.ec.europa.eu/#

[26] COMMISSION IMPLEMENTING DECISION of 17.12.2015 on a standardisation request to the European standardisation organisations as regards ecodesign requirements on material efficiency aspects for energy-related products in support of the implementation of Directive 2009/125/EC of the European Parliament and of the Council (Brussels, 17.12.2015 C(2015) 9096 final)

- IEEE 1680.2, 2012 IEEE Std 1680.2™-2012. IEEE Standard for Environmental Assessment of Imaging Equipment. The Institute of Electrical and Electronics Engineers.
- IEEE 1680.3, 2012 IEEE Std 1680.3™-2012. IEEE Standard for Environmental Assessment of Televisions. The Institute of Electrical and Electronics Engineers.
- ISO 22628. Road vehicles—Recyclability and recoverability—Calculation method. EN 15643 standard for buildings, which refers to recycling and resource efficiency aspects. 2002.
- ISO 14021. Environmental labels and declarations — self-declared environmental claims (Type II environmental labelling). 1999
- ONR 192102 Durability mark for electric and electronic appliances designed for easy repair (white and brown goods).
- IEC 61215 Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval.
- EPEAT criteria for smartphones, EPA, USA http://www2.epa.gov/sites/production/files/documents/epeat_gp_rev.pdf
- UL 110 Standard for Sustainability for Mobile Phones, March 14, 2012 is currently in the process to become an ANSI standard with some minor modifications http://ulstandards.ul.com/standard/?id=110_1
- IEEE 1874: Standard for Documentation Schema for Repair and Assembly of Electronic Devices. http://standards.ieee.org/findstds/standard/1874-2013.html
- VDI-guideline 2343 'Recycling of electric and electronic appliances', DGAW Association, Netzwerk Großbeerenstraße Association

1.2.5 Safety

Standards relating to safety have been (or are to be) harmonised and are referenced in section 1.3 regarding "EU legislation".

A harmonised standard is a European standard developed by a recognised European Standards Organisation: CEN, CENELEC, or ETSI. It is created following a request ("mandate") from the European Commission to one of these organisations. Manufacturers, other economic operators, or conformity assessment bodies can use harmonised standards to demonstrate that products, services, or processes comply with relevant EU legislation[27].

The references of harmonised standards must be published in the Official Journal of the European Union.

1.2.6 Standards at Member State level

The analysis shows no other relevant technical (performance) standards at member State level.

National standardisation bodies within the EU, are obliged to adopt and publish all European Standards as identical national Standards (prefixed with country specific code) and to withdraw pre-existing national Standards that are in conflict.

However, national standardisation bodies have the option to adopt and publish international standards. The international standard then receives a national prefix, thus becoming BS-ISO in case of UK standards, or DIN-ISO in case of German standards, or NEN-ISO in case of Dutch standards, etc.

[27] https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards_en

1.2.7 Third country test standards

USA Test procedure for compressors

Since May 5, 2015 US DoE has published a Test procedure for compressors, linked to the proposed rulemaking discussed in section 1.5 Pending the outcome of the rulemaking process in the USA there may be a DOE issued standard for air compressors (see also section 1.5).

The applicability of the test procedure is limited to compressors that meet the following criteria (the sections refer to the rest of the document – see integral text on the DOE website):

- Are air compressors, as defined in section III.B.2;
- Are rotary or reciprocating compressors, as defined in section III.B.3;
- Are driven by a brushless electric motor, as defined in section III.B.4;
- Are distributed in commerce with a compressor motor nominal horsepower greater than or equal to 1 and less than or equal to 500 horsepower (hp) as defined in section III.B.5; and
- Operate at a full-load operating pressure of greater than or equal to 31 and less than or equal to 225 pounds per square inch gauge (psig), as defined in section III.B.6.

The proposed test method can be found at:

https://www.regulations.gov/#!documentDetail;D=EERE-2014-BT-TP-0054-0001

The test procedure is very much based on ISO 1217, with some deviations to better align with the proposed rule. It proposes to test at three points for variable-speed compressors,40-percent, 70-percent, and 100-percent of full-load actual volume flow rate, calculate isentropic efficiency at each point, and weight those into a single metric (aligned with EU proposal for standard air). The variable-speed tested points in the CAGI data sheets may not necessarily line up with the test points in the test procedure NOPR.

General remarks on USA standard development

In contrast to the EU, the US does not refer to “harmonised” standards, but instead develops them though a government-managed rulemaking process in which several rounds of documents are released to invite and respond to comments from the public. Anyone may submit comments, but most are received from manufacturers, purchasers of the equipment, electrical utilities, efficiency advocacy organizations, and other parties with a clear interest in the rule’s outcome. Based on those comments and its own analysis, DOE issues a proposed rule and, eventually, a final rule.

Occasionally, DOE may deviate from this usual notice-and-comment process by entering into a “negotiated rulemaking.” A negotiated rulemaking invites relevant parties of varying interests to a series of meetings in hopes of establishing a consensus to serve as the basis of the standard. DOE is not currently holding negotiations for air compressors. As a result, the next likely step is for DOE to issue either a draft analysis or a proposed standard for the public to comment on.

Regardless of whether DOE follows the centralized, notice-and-comment process or opens negotiations, DOE has historically attempted to adhere to established industry standards and conventions in order to minimize burden to market participants.

DOE considers the benefits of harmonization with other regions, particularly where manufacturers participate in both markets, but is still obligated to justify a rule on the basis of its own criteria, which include economic benefit to the public, cost to manufacturers, and technological feasibility.”

Chinese Test procedure for compressors

In China the standard GB/T 3853-1998 has to be applied for performance assessment of compressors covered by the Chinese rule or regulation, but according information by CLASP this standard is linked to the international ISO 1217 standard.

1.2.8 Any other relevant standard

This section deals with any other standard relevant for the products regarding the technical, economic, environmental and ecodesign analysis carried out in this study.

BL 300-2016[28]

In 2016 CAGI published the reviewed CAGI BL300-2014 Simplified Acceptance Test of Electric Driven, Low Pressure Air Blower Packages. It was developed by CAGI as a response to a need for acceptance tests for both positive displacement and centrifugal blowers (these are low pressure compressors).

The foreword of the BL 300 document[29] explains the history and intentions of the standard:

In 2010, CAGI members were approached by the Consortium for Energy Efficiency (CEE) to address the need for test standards for centrifugal and positive displacement blower packages among the CEE membership, which comprises the electricity provider energy efficiency program administrators. A working group within CAGI's Blower Section formed soon after. The working group embarked on a standard development project which initially resulted in the release of the BL 5389 standard in 2013 as an interim step.

The BL 5389 standard was intended to eventually become an annex to the ISO 5389 standard, which provides an extremely detailed, complex procedure to test and rate turbo compressor blowers[30]. The new BL 5389 standard provides an easily integrated, cost effective, yet highly accurate "wire to air" approach to testing. It is applicable to all dynamic blower packages in all industrial and municipal air applications.

While the standard is intended for use with all types of turbo compressor blower packages, it will be particularly useful for machines that are manufactured in batches or in continuous production quantities.

The working group continued to pursue its mandate of developing a standard that addressed both dynamic and positive displacement blowers.

A section of material relevant specifically to positive displacement blowers (primarily lobe and screw type blowers) was developed next. The addition of another section of material that provided a means of comparing the performance of the two broad types of blowers, dynamic and positive displacement, followed shortly thereafter.

All three sections were combined to form the current BL 300 standard, which was approved as a CAGI standard and was released in 2014.

Pneurop PN 2:2015, Guideline for verifying performance of low pressure compressors

In parallel to the development of the BL300 by CAGI, a "Low Pressure Working Group" (LPWG), commissioned by Pneurop worked on an informative "Guideline for verifying performance of low pressure compressors". The document is approved by Pneurop (June 2015) but is not made public in anticipation of a new document by a joint CAGI/Pneurop WG that has been created to investigate the possible alignment of both documents.

The objected target for the LPWG that developed the guideline was to provide a document under the premise to achieve comparability (of guarantee performance) for all kinds of low pressure compressors.

The Pneurop guideline defines "low pressure" by the following limits:

1. inlet pressure p1: 0.5 bar $\leq$ p1 $\leq$ 1.5 bar

[28] http://www.cagi.org/pdfs/CAGIPneuropBL3002016.pdf

[29] http://www.cagi.org/pdfs/CAGI_BL_300.pdf

[30] This code was developed as part of a broader standard that addresses all types of blowers and as an Annex (G) to ISO 5389, Turbo compressors — Performance test code, Second edition, 2005-12-15. The existing code was simplified to account for the lack of interstage cooling.

2. pressure increase: 0.1 bar $\leq$ Δp $\leq$ 3.5 bar
3. pressure ratio: p2/p1 $\leq$ 4.5

The guideline proposed default conditions for publishing technical data:

- inlet air pressure: 101.325 kPa (1.01325 bar(a))
- inlet air temperature: 20ºC
- inlet relative humidity: 0%
- temperature of coolants at package inlet: 20ºC

The object of the guarantee is:

- inlet volume flow rate;
- absolute outlet pressure (measured at outlet point);
- machine power input under load;
- specific energy consumption;
- idling power consumption;
- standby power consumption.

The LPWG "Guideline for verifying the performance of low pressure compressors" advises for compressors without internal compression to use the combined isentropic and isochoric reference process (see Definitions 3.4.6.3) as for specific types of compressors, such as the lobe compressor, part of the compression process is assumed to occur under isochoric conditions (pressure changes while the volume stays constant) and.

Equation 5 Isentropic (and isochoric) power from LP WG

$$W_{(comb)} = p_1 * V_s * \left[\frac{p_2/p_1}{v_i} + \frac{\kappa}{\kappa - 1} \left(\frac{1}{\kappa} \, {v_i}^{\kappa - 1} - 1 \right) \right]$$

where:

$W_{(comb)}$ = the combined isentropic and isochoric work of a low pressure displacement compressor with or without internal compression

p_1 = Inlet pressure (Pa)
V_s = Volume flow (not mass flow) (m^3/s)
p_2/p_1 = Pressure ratio
v_1 = internal volume ratio (-). With v_1 equal to 1 the reference process is isochoric, with v_1 equal to $(p_2/p_1)^{1/\kappa}$ it is isentropic
κ = ratio of specific heat capacities (for dry air close to 1 bar pressure: 1.4)

Joint CAGI/Pneurop WG on low pressure[31]

The work started in August 2015, and was finalised in June 2016. The document is approved by Pneurop and CAGI and is now brought to ISO as a New Work Item Proposal.

Extrapolation to higher pressures (to 5 or 7 bar(a)) is not sought because of limitations of the method (e.g. no cooling during compression).

American Petroleum Institute

The America Petroleum Institute has published several standards related to product design and performance of compressors used in the petroleum and gas industry.

API STANDARD 617

[31] http://www.cagi.org/pdfs/CAGIPneuropBL3002016.pdf

Axial and Centrifugal Compressors and Expander-compressors for Petroleum, Chemical and Gas Industry Services

Axial and Centrifugal Compressors and Expander-Compressors covers the minimum requirements for centrifugal compressors used in petroleum, chemical, and gas industry services that handle air or gas, including process gear mounted. It does not apply to fans or blowers that develop less than 34 kPa (5 psi) pressure rise above atmospheric pressure; these are covered by API Standard 673. This standard also does not apply to packaged, integrally-geared centrifugal air compressors, which are covered by API Standard 672.

Section 5.2.4 of API 617 requires the vendor to supply curves for variable-speed compressors that shall include the following: discharge pressure; power; polytropic head; and polytropic efficiency versus inlet capacity (from predicted surge point to 115% rated capacity) at minimum operating speed and 80%, 90%, 100%, and 105% speed, and indicating the effect of specified inlet pressures, temperatures, and molecular weights. Any specified operating points shall be noted within the envelope of the performance curve predicted.

API 617 does not state the reference gas conditions as API 617 is intended for use in the petroleum and gas industries and the operating conditions shall be defined, and thus the performance shall be established, for each specific intended use (performance depends on type of gas, pressure ratio, ambient conditions, etc.).

In section 4.3.3 Optional test it is stated that the compressor shall be performance tested in accordance with ASME PTC 10-1997, ISO 5389 or other approved national standard. A minimum of five points, including surge and overload, shall be taken at normal speed. For variable-speed machines, additional points may be specified.

For variable speed or variable vane machines, head and capacity shall have zero negative tolerance at the normal operating point (or other point as specified), and the power at this point shall not exceed 104% of the vendor predicted shaft power value. This tolerance shall be inclusive of all test tolerances.

API Standard 618

Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services

Covers the minimum requirements for reciprocating compressors and their drivers used in petroleum, chemical, and gas industry services for handling process air or gas with either lubricated or non-lubricated cylinders. Compressors covered by this standard are of low to moderate speed and in critical services. Also covered are related lubricating systems, controls, instrumentation, intercoolers, aftercoolers, pulsation suppression devices, and other auxiliary equipment.

API Standard 672

Packaged, Integrally Geared Centrifugal Air Compressors for Petroleum, Chemical, and Gas Industry Services

Covers the minimum requirements for constant-speed, packaged, general purpose integrally geared centrifugal air compressors, including their accessories. This standard is not applicable to machines that develop a pressure rise of less than 0.35 bar (5.0 psi) above atmospheric pressure, which are classed as fans or blowers.

API Standard 681

Liquid Ring Vacuum Pumps and Compressors for Petroleum, Chemical, and Gas Industry Services

Defines the minimum requirements for the basic design, inspection, testing, and preparation for shipment of liquid ring vacuum pump and compressor systems for service in the petroleum, chemical, and gas industries. It includes both vacuum pump and compressor design and system design.

1.2.9 Comparative analysis for overlapping test standards

There are no overlapping standards for the primary and secondary performance parameters as most can be traced back to ISO 1217 and ISO 5389.

1.2.10 Mandates to CEN/CENELEC

As stated in section 1.3.9 possible ecodesign requirements for standard air compressor packages were discussed in the Consultation Forum on 23 October 2014.

However, no further proposal has been put forward by the Commission and so far no mandate has been issued by the European Commission to European Standardisation organisations (CEN, CENELEC, ETSI) to develop European (EN) standards that could be used for compliance with possible forthcoming legislation[32].

The mandate, if issued, must take into account elements that are essential to the requirements proposed. This may mean that if indeed the minimum energy efficiency is to be expressed using isentropic efficiency, the EN standard to be developed must set out a methodology and the conditions to establish this. Annex H to ISO 1217 describes such an approach. Other possible requirements, such as the "cycle energy requirement", must also be taken into account in the mandate and the standard to be developed from that.

Publication of a mandate related to (performance assessment of) low pressure and/or oil-free compressor packages is still a number of steps away in time and depends on the outcome of the study, the opinion of the European Commission whether or not to start the regulatory process and the opinion of stakeholders, such as voiced in a Consultation Forum meeting. If a mandate is issued, it will most likely be taken up by CEN/TC 233.

1.2.11 Tolerances

ISO 1217

ISO 1217 describes in Annex C (normative) a Simplified acceptance test for electrically driven packaged displacement compressors including tolerances to be applied.

The test conditions shall be as close as is reasonably possible to the specified conditions and the deviations from these shall not exceed the limits indicated in Table C.1.

Table 10 Table C.1 – Maximum deviations from specified values during an acceptance test

Inlet pressure	± 10%
Discharge pressure	± 2%
External coolant quantity	± 10%
Inlet temp. of external air coolant [a]	± 10 K
Inlet temp. of external liquid coolant [a]	± 5 K
Liquid injection temperature	± 5 K
[a] For multi-stage compressors with inter cooler, the difference between gas inlet temperature and external coolant temperature shall be limited to ± 2 K in the case of liquid and ± 4 K for air	

The compressor under test shall be deemed acceptable provided the results obtained do not differ from the specified performance by more than the allowances given in Table C.2.

Table 11 Table C.2. – Maximum deviations permissible at test

Volume flow rate at specified conditions	Volume flow rate	Specific power requirement	Power requirement (at zero volume flow rate or at pressure ratio of 1) [a]
(m^3/s) x 10^{-3}	%	%	%
$0 < q_v \leqslant 8.3$	± 7	± 8	± 10
$8,3 < q_v \leqslant 25$	± 6	± 7	± 10

[32] In this case a mandate of the European Commission to the European Standardization Organisations is preferred to start the process of developing an European (EN) standard that can be harmonized.

25 < $q_v \leqslant$ 250	± 5	± 6	± 10
q_v > 250	± 4	± 5	± 10

NOTE The tolerance values in this table cover and include manufacturing tolerances of the compressor and tolerances relating to the measurements taken during the test.
[a] Where specified, the manufacturer shall state the method used

Isentropic efficiency is now included in ISO 1217 through publication of Annex H in 2016. As isentropic efficiency can be calculated from specific power requirement (for a given inlet/outlet pressure) and vice versa, their relative tolerances are directly related, but require conversion as isentropic efficiency is proportional to the reciprocal of the specific power requirement.

Annex H of ISO 1217 presents the tolerances for P_{spec} (specific power requirement) and isentropic efficiency ηi_{sen}.

Table 12 Tolerances of P_{spec} and isentropic efficiency (Table H.3 of ISO1217-A1-2017)

Volume flow rate at specified conditions $(m^3/s)\cdot 10^{-3}$	**P_{spec} tolerances [%]**		**corresponding η_{isen} tolerances [%]**	
	U_P = upper limit	*L_P = lower limit*	*L_η = upper limit*	*U_η = lower limit*
0 < $q_V \leq$ 8.3	+8	-8	-7,41	8,7
8.3 < $q_V \leq$ 25	+7	-7	-6,54	7,53
25 < $q_V \leq$ 250	+6	-6	-5,66	6,38
$q_V \geq$ 250	+5	-5	-4,76	5,26

The tolerances on isentropic efficiency in are percentages of percentages. To calculate the tolerance on the isentropic efficiency in percentage points, the tolerance percentage is multiplied with the percentage value of the isentropic efficiency.

ISO 5389

ISO 5389 deals with tolerances differently and provides an extensive method for verifying guaranteed performances. ISO 5389 treats measurement and manufacturing tolerances differently: In section 4.5 Guarantee comparison ISO 5389 states: *"In case of an acceptance test, the test results measured and converted to the guarantee conditions shall be assessed against the values guaranteed (see Clause 8), making allowance for the limits of measuring uncertainties (see 6.4).Any manufacturing tolerances for the guarantee shall be deemed to constitute a component of the contract of supply and not of this International Standard."*

1.2.12 Other compressor related standards[33]

Besides the standards presented above there are numerous other standards that may be used to define, describe and establish compressor aspects. These other standards are presented below, grouped into 'petrochemical standards' and ' standards for ancillary equipment'.

These standards are less relevant for ecodesign purposes as these mostly define compressor performance and characteristics to facilitate procurement and trade.

Table 13 'Petrochemical' standards

EN ISO 10439:2002	Petroleum, chemical and gas service industries—Centrifugal compressors
ISO/DIS 10439-1	Petroleum, petrochemical and natural gas industries—Axial and centrifugal compressors and expander-compressors—Part 1: General requirements
ISO/DIS 10439-2	Petroleum, petrochemical and natural gas industries—Axial and centrifugal compressors and

[33] The list of standards in this section has not been updated since the Lot 31 Task 1-5 report of 22 May 2014

	expander-compressors—Part 2: Non-integrally geared centrifugal and axial compressors
ISO/DIS 10439-3	Petroleum, petrochemical and natural gas industries—Axial and centrifugal compressors and expander-compressors—Part 3: Integrally geared centrifugal compressors
ISO/DIS 10439-4	Petroleum, petrochemical and natural gas industries—Axial and centrifugal compressors and expander-compressors—Part 4: Expander-compressors
ISO 10440-1:2007	Petroleum, petrochemical and natural gas industries—Rotary-type positive-displacement compressors—Part 1: Process compressors
EN ISO 10440-2:2001	Petroleum and natural gas industries - Rotary-type positive-displacement compressors - Part 2: Packaged air compressors (oil-free) (ISO 10440-2:2001)
EN ISO 10442:2002	Petroleum, chemical and gas service industries—Packaged, integrally geared centrifugal air compressors
ISO 13631:2002	Petroleum and natural gas industries—Packaged reciprocating gas compressors
ISO/NP 13707	Petroleum and natural gas industries—Reciprocating compressors
ISO 13707:2000	Petroleum and natural gas industries—Reciprocating compressors

Table 14 Pneumatic tools

ISO 2787:1984	Rotary and percussive pneumatic tools—Performance tests
ISO 3857-3:1989	Compressors, pneumatic tools and machines—Vocabulary—Part 3: Pneumatic tools and machines
ISO/DIS 3857-4	Compressors, pneumatic tools and machines—Vocabulary—Part 4: Air treatment
ISO 5391:2003	Pneumatic tools and machines—Vocabulary
ISO 5393:1994	Rotary tools for threaded fasteners—Performance test method

Table 15 Miscellaneous / ancillary equipment standards

ISO 3857-1:1977	Compressors, pneumatic tools and machines—Vocabulary—Part 1: General
ISO 3857-2:1977	Compressors, pneumatic tools and machines—Vocabulary—Part 2: Compressors
ISO 7183:2007	Compressed-air dryers—Specifications and testing
ISO 8573-1:2010	Compressed air—Part 1: Contaminants and purity classes
ISO 8573-2:2007	Compressed air—Part 2: Test methods for oil aerosol content
ISO 8573-3:1999	Compressed air—Part 3: Test methods for measurement of humidity
ISO 8573-4:2001 / Cor 1:2002	Compressed air—Part 4: Test methods for solid particle content
ISO 8573-5:2001	Compressed air—Part 5: Test methods for oil vapour and organic solvent content
ISO 8573-5:2001	Compressed air—Part 5: Test methods for oil vapour and organic solvent content
ISO 8573-7:2003	Compressed air—Part 7: Test method for viable microbiological contaminant content
ISO 8573-8:2004	Compressed air—Part 8: Test methods for solid particle content by mass concentration
ISO 8573-9:2004	Compressed air—Part 9: Test methods for liquid water content
ISO 12500-1:2007	Filters for compressed air—Test methods—Part 1: Oil aerosols
ISO 12500-2:2007	Filters for compressed air—Test methods—Part 2: Oil vapours
ISO 12500-3:2009	Filters for compressed air—Test methods—Part 3: Particulates
ISO 12500-4:2009	Filters for compressed air—Methods of test—Part 4: Water
ISO 3857-1:1977	Compressors, pneumatic tools and machines—Vocabulary—Part 1: General
ISO 3857-2:1977	Compressors, pneumatic tools and machines—Vocabulary—Part 2: Compressors
ISO 5388:1981	Stationary air compressors—Safety rules and code of practice

ISO 5390:1977	Compressors—Classification	
ISO 5941:1979	Compressors, pneumatic tools and machines—Preferred pressures	
ISO/DIS 11011	Compressed air—Energy efficiency—Assessment	This standard applies to compressed air systems, not energy efficiency of the compressor package solely
EN 12583:2000	Gas supply systems - Compressor stations - Functional requirements	

1.3 EU Legislation

Apart from the Working Document on standard air compressor packages, presented to the Ecodesign Consultation Forum on 23 October 2014, no other legislation at EU level or at MS level introducing requirements for main ecodesign parameters has been identified.

Certain components used in compressor packages such as electric motors and fans are covered by regulations introducing minimum requirements.

The equipment is of course covered by directives or measures relating to safety (Machinery, pressure equipment, pressure vessels, electromagnetic compatibility, electrical safety, explosive atmospheres) and occupational health or environment (machinery, outdoor noise).

Environmental legislation like RoHS, WEEE, Waste and Industrial Emissions Directive do not apply directly to (industrial) compressors, but may be indirectly relevant. RoHS and WEEE may apply to some (smaller) compressors sold through DIY stores.

There is no EU legislation of energy labelling or ecolabelling of compressors, nor are Voluntary Agreements identified.

The following sections describe more generic EU legislation, which may be relevant for low pressure and/or oil-free compressors.

1.3.1 Machinery Directive 2006/42/EC

The Machinery Directive 2006/42/EC provides the regulatory basis for the harmonisation of the essential health and safety requirements for machinery at European Union level. Machinery can be described as "an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application".

The essential requirements related to environmental aspects may address noise, vibrations, radiation, emissions of hazardous materials and substances (Annex 1, item 1.5).

Essentially performing a dual function, the Directive not only promotes the free movement of machinery within the Single Market, but also guarantees a high level of protection to EU workers and citizens. Being a "New Legal Framework" Directive, it promotes harmonisation through a combination of mandatory health and safety requirements and voluntary harmonised standards.

Such directives apply only to products which are intended to be placed (or put into service) on the EU market for the first time.

The Machinery Safety Directive 2006/42/EC was published on 9th June 2006 and it is applicable from 29th December 2009, replacing the Machinery Directive 98/37/EC.

EU Machinery directive 2006/42/EC[34], referring to the following standards[35]:

[34] Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast) OJ No L 157, 9 June 2006

[35] http://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/machinery/index_en.htm

- EN 1012-1:2010 Compressors and vacuum pumps – Safety requirements - Part 1: Air compressors
- EN 1012-3:2013 Compressors and vacuum pumps –Safety requirements - Part 3. Process compressors
- EN ISO 12100-1:2003 AMD 1 2009, Safety of Machinery – Basic concepts, General principles for design – Part 1: Basic Terminology, Methodology
- EN ISO 12100-2:2003 AMD 1 2009, Safety of Machinery – Basic concepts, General principles for design – Part 2: Technical Principles
- EN ISO 2151:2008 (ISO 2151:2004) - Acoustics—Noise test code for compressors and vacuum pumps—Engineering method (Grade 2)

Partly completed machinery

The machinery Directive also covers partly completed machinery, which is relevant to this study as compressors may be placed on the market without electric motor or other main components.

For Directive 2006/42/EC it is important that the suppliers makes available a "Declaration of incorporation" which requires a sentence declaring which essential requirements of this Directive are applied and fulfilled and that the relevant technical documentation is compiled in accordance with part B of Annex VII of Directive 2006/42/EC, and, where appropriate, a sentence declaring the conformity of the partly completed machinery with other relevant Directives.

The relevant technical documentation for partly completed machinery must show which requirements of this Directive are applied and fulfilled. It must cover the design, manufacture and operation of the partly completed machinery to the extent necessary for the assessment of conformity with the essential health and safety requirements applied.

1.3.2 PED - Pressure Equipment Directive 2014/68/EU

The Pressure Equipment Directive (PED) provides the legislative framework for equipment subject to a pressure hazard. The main aims are to harmonise standards regarding the design, manufacture, testing and conformity assessment of pressure equipment and assemblies of pressure equipment.

1.3.3 Simple Pressure Vessels Directive 2014/29/EU

The Directive applies to series produced, unfired pressure vessels of welded construction which are intended to contain air or nitrogen at an internal gauge pressure greater than 0.5 bar. There are also limits to the maximum working pressure and the minimum working temperature, and it has specific requirements covering the geometry of the design and the materials that can be used.

The main application of vessels covered by the Directive is to provide a pressurised reservoir to smooth the air supply from a compressor and minimise the change in pressure with variations in the load or flow rate. The compressed air from the vessel could be used as part of a paint spraying system, or to drive various pneumatic tools, fluid logic systems and actuators in a factory.

Standards harmonized under the predecessor EU Directive 87/404/EC and 87/404/EEC are:

- EN 764-1 to 7, Pressure equipment;
- EN 286-1 to 4, Simple, unfired pressure vessels designed to contain air or nitrogen.

1.3.4 EMC – Electromagnetic Compatibility Directive 2014/30/EU

The EMC is in place to ensure that electrical equipment is designed such that it doesn’t interfere with or get disturbed by other electrical equipment and thus functions properly.

The main objective of the Directive 2014/30/EU is regulate the compatibility of equipment regarding EMC. It requires:

- equipment (apparatus and fixed installations) to comply with EMC requirements when it is placed on the market and/or taken into service;
- the application of good engineering practice for fixed installations, with the possibility for the competent authorities of Member States to impose measures if non-compliance is established.

The EMC Directive first limits electromagnetic emissions of equipment in order to ensure that, when used as intended, such equipment does not disturb radio and telecommunication as well as other equipment. The Directive also governs the immunity of such equipment to interference and seeks to ensure that this equipment is not disturbed by radio emissions when used as intended.

Before equipment is placed on the market (including both apparatus and fixed installations) they must be shown to meet the requirements set out in the EMC Directive.

Standards harmonized under the predecessor EU Directive 2004/108/EC are:

- EN 61000-6-2:2005, Electromagnetic compatibility (EMC) - PART 6-2: Generic Standards – Immunity for Industrial Environments
- EN 61000-6-4:2006, Electromagnetic compatibility (EMC) - PART 6-4: Generic Standards – Emission standards for Industrial Environments

1.3.5 LVD - Low Voltage Directive 2014/35/EU

The Low Voltage Directive (LVD), also counting its predecessors, is one of the oldest Single Market Directives adopted before the "New" or "Global" Approach. However, it does characterise both with a conformity assessment procedure applied to equipment before placing on the Market and with Essential Health and Safety Requirements (EHSRs) which such equipment must meet either directly or by means of harmonised standards. The LVD ensures that electrical equipment within certain voltage limits both provides a high level of protection for European citizens and enjoys a Single Market in the European Union.

The Directive covers electrical equipment with a voltage between 50 and 1 000 V for alternating current and between 75 and 1 500 V for direct current. It should be noted that these voltage ratings refer to the voltage of the electrical input or output, not to voltages that may appear inside the equipment. For most electrical equipment, the health aspects of emissions of Electromagnetic Fields are also under the domain of the Low Voltage Directive.

For electrical equipment within its scope, the Directive covers all health and safety risks, thus ensuring that electrical equipment is safe in its intended use. Guidelines on application and Recommendations are available - including LVD Administrative Co-operation Working Group (LVD ADCO) documents and recommendations - as well as European Commission opinions within framework of the Directive.

In respect of conformity assessment, there is no third party intervention, as the manufacturer undertakes the conformity assessment. There are "Notified Bodies" which may be used to provide reports in response to a challenge by a national authority as to the conformity of the equipment.

Standards harmonized under the predecessor EU Directive 2006/95/EC are:

- EN 60034- Part 1 to 30, Rotating Electrical Machines – Rating and Performance
- EN 60204-1:2009, Safety of Machinery – Electrical Equipment of Machines – Part 1: General Requirements
- EN 60439-1:2004, Low-voltage switchgear and control gear assemblies – Part 1: Type tested and partially type tested assemblies

1.3.6 Outdoor Noise Directive 2000/14/EC

Directive 2000/14/EC, as amended by 2005/88/EC, on the noise emission in the environment by equipment for use outdoors defines compressors as follows:

Any machine for use with interchangeable equipment which compresses air, gases or vapours to a pressure higher than the inlet pressure. A compressor comprises the bare compressor itself, the prime mover and any component or device supplied, which is necessary for safe operation of the compressor.

Excluded are the following categories of device:

1. fans, i.e. devices producing air circulation at a positive pressure of not more than 110 000 Pascals;
2. vacuum pumps, i.e. devices or appliances for extracting air from an enclosed space at a pressure not exceeding atmospheric pressure;
3. gas turbine engines.

The administrative and legal position is given in the Directive 2000/14/EC of the European Parliament and of the Council of 8 May 2000, on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors. Noise emissions of outdoor machinery are regulated by European directive 2000/14/EC. This directive lays down minimal requirements (such as noise marking, noise emission limits) for outdoor machinery that must be respected before equipment can be placed on the European market. It represents a conventional ("command-and-control") regulatory approach. The directive has been amended by the Directive 2005/88/EC of the European Parliament and of the Council of 14 December 2005 and by the Regulation (EC) 219/2009.

EU Directive 2000/14/EC, Outdoor Noise Emission, referring to the following standards:

- EN ISO 3744:2009, Determination of sound power levels of noise sources using sound pressure – Engineering method
- EN ISO 2151:2004, Noise test code for compressors and vacuum pumps – Engineering method (Grade 2) (ISO 2151:2004).

EU Directive 2004/26/EC, Emission standard for non-road engines – Stage III levels implemented from 2006 to 2013, Stage IV as from 2014

US Federal Emission standard for non-road engines – Tier III levels implemented from 2006 to 2008, Tier IV levels as from 2008 to 2015

1.3.7 Medical devices – general: EU Directive 93/42/EC

For compressors in dental practices or hospitals EU Directive 93/42/EC, referring to the following standards, may be relevant:

- EN ISO 13845:2000, Plastics Piping system – Test method for leak-tightness under internal pressure
- EN ISO 14971:2007, Medical Devices – Application of risk management to Medical Devices

1.3.8 Ecodesign Directive 2009/125/EC plus implementing Regulations

The Ecodesign Directive itself does not introduce requirements for compressors or any specific product, but sets a legislative framework for implementing measures.

Most relevant is the work resulting from the current and preceding Lot 31 study, but the measures aimed at electric motors and fans are also relevant as these cover components used in compressors.

1 - Working Document for standard air compressor packages

The first lot 31 study resulted in a Working Document, which presented a Commission proposal for measures aimed at standard air compressor packages, that was discussed in a Consultation Forum meeting on 23 October 2014.

Several stakeholders responded on that proposal preceding, during and after the meeting. The position of Pneurop before the meeting was that the proposed requirements were too stringent and Pneurop proposed to follow the business-as-usual scenario, e.g. without extra regulation. This however could lead to the EU becoming a dumping ground for inefficient compressors that are no longer allowed on other markets (e.g. China, possibly USA – see section 1.5). After the meeting, Pneurop agreed with minimum requirements (although less strict than in the WD).

So far no Working Document has been brought into Interservice Consultation, so the product groups is probably still in the Impact Assessment phase (status February 2017).

2 - Electric motors Regulation 640/2009

The Electric motor Regulation is relevant for electrically driven compressors as the motor may be included in the definition of what comprises a 'compressor' (just the bare compressor or the compressor package).

In Regulation 640/2009 the definition of the electric motor is:

'Motor' means an electric single speed, three-phase 50 Hz or 50/60 Hz, squirrel cage induction motor that:

- has 2 to 6 poles,
- has a rated voltage of U_N up to 1 000 V,
- has a rated output P_N between 0.75 kW and 375 kW,
- is rated on the basis of continuous duty operation.

Excluded are motors that:

- motors designed to operate wholly immersed in a liquid;
- motors completely integrated into a product (for example gear, pump, fan or compressor) of which the energy performance cannot be tested independently from the product;
- motors specifically designed to operate in non-standard ambient conditions (see Regulation for more specific descriptions of these conditions);
- brake motors.

The ecodesign requirements address the energy efficiency of the motor, expressed in IE levels of efficiency. The ecodesign requirements apply in accordance with the following timetable:

1) from 16 June 2011, all motors placed on the market shall not be less efficient than the IE2 efficiency level (IE levels defined in Annex I, point 1);
2) from 1 January 2015: motors with a rated output of 7,5-375 kW shall not be less efficient than the IE3 efficiency level or meet the IE2 efficiency level and be equipped with a variable speed drive.
3) from 1 January 2017: all motors with a rated output of 0,75-375 kW shall not be less efficient than the IE3 efficiency level, or meet the IE2 efficiency level and be equipped with a variable speed drive.

A review study of this regulation ran until July 2014 and Commission Working Documents have been discussed in a Consultation Forum meeting on 29 September 2014.

Up to now no Working Document has been brought into Interservice Consultation, so the product groups is probably still in the Impact Assessment phase (status February 2017).

3 - Fan Regulation 327/2011

In Regulation 327/2011 'Fan' means a rotary bladed machine that is used to maintain a continuous flow of gas, typically air, passing through it and whose work per unit mass does not exceed 25 kJ/kg, and which:

- is designed for use with or equipped with an electrical motor with an electric input power
- between 125 W and 500 kW (≥ 125 W and ≤ 500 kW) to drive the impeller at its optimum energy efficiency point,
- is an axial fan, centrifugal fan, cross flow fan or mixed flow fan,
- may or may not be equipped with a motor when placed on the market or put into service;

Excluded are fans that:

- products with a sole electric motor of 3 kW or less where the fan is fixed on the same shaft used for driving the main functionality;
- laundry and washer dryers ≤ 3 kW maximum electrical input power;
- kitchen hoods < 280 W total maximum electrical input power attributable to the fan(s).

The ecodesign requirements address the energy efficiency of the driven fan. The ecodesign requirements apply in accordance with the following timetable:

1. first tier: from 1 January 2013, ventilation fans shall not have a lower target energy efficiency than as defined in Annex I, Section 2, Table 1 (the target values differ per fan type);
2. second tier: from 1 January 2015, all fans shall not have a lower target energy efficiency than as defined in Annex I, Section 2, Table 2.

A review study of this regulation is recently completed (March 2015) and Commission Working Documents have been discussed in a Consultation Forum meeting on 30 April 2015.

So far no Working Documents have been brought into Interservice Consultation, so the product groups are probably still in the Impact Assessment phase (status February 2017).

High pressure / low volume flow fans

After the discussion of the Working Documents in the Consultation Forum, stakeholder association EVIA brought forward the point that certain high pressure low volume flow fans (HPLV) would not be able to meet requirements as these are based on standard fans (operating at smaller pressure difference) and EVIA suggested a dedicated approach, for energy efficiency requirements[36].

As HPLV fans are actually operating on the 'other' side of the threshold of the pressure ratio of 1.1 between fans and (low pressure) compressors, it would appear logical to try to align the requirements for HPLV and low pressure compressors, so that no sudden disruption is created (resulting in an unbalanced playing field where it would be beneficial to rate a product as HPLV rather than low pressure compressor or vice versa).

1.3.9 Energy Labelling Directive 2010/30/EU

The recast Energy Labelling Directive 2010/30/EU was adopted by the European Parliament and Council the 19th May 2010.

The scope is energy-related products in household, commercial and industrial sectors. This implies that the Directive covers any good having an impact on energy consumption during use. These products could not only consume energy but could also "have a significant direct or indirect impact" on energy savings.

Energy labelling requirements are already in force for a large number of (business-to-consumer) products. For typical business-to-business products introduction of energy labelling has been considered less effective as professional buyers are considered knowledgeable.

However, the Commission has made clear that introduction of energy labels for typical commercial or industrial products should remain a possibility to be addressed in preparatory studies. This study will therefore also consider (in Task 7) labelling of low pressure and oil-free compressor packages.

[36] HPLV fans are to be defined as such on the basis of their specific speed. Nonetheless, the overall definition of a fan includes a pressure ratio of max 1.1 so all equipment beyond that ratio, is not a fan, nor HPLV fan.

1.3.10 Ecolabel Regulation 66/2010

The Commission summary [37] for the EU Ecolabel states the following:

EU Ecolabel may be awarded to products and services which have a lower environmental impact than other products in the same group. The label criteria were devised using scientific data on the whole of a product's life cycle, from product development to disposal.

The label may be awarded to all goods or services distributed, consumed or used on the Community market whether in return for payment or free of charge. It does not apply to medicinal products for human or veterinary use, or to medical devices.

The system was introduced by Regulation (EEC) No 880/92 and amended by Regulation (EC) No 1980/2000. This Regulation (EEC) No 66/2010 aims to improve the rules on the award, use and operation of the label.

No interest in EU Ecolabelling of air compressors was identified.

1.3.11 Waste Electrical and Electronic Equipment Directive

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast) defines WEEE as 'waste electrical and electronic equipment' thus covering waste of:

equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1 000 volts for alternating current and 1 500 volts for direct current;

Although the above definition in general would cover compressors (packages) within the scope of this study, Article 2.3 and 2.4 identify exclusions, one of which is 'large-scale stationary industrial tools' (article 2.4.b).

'Large-scale stationary industrial tools' is defined as:

a large size assembly of machines, equipment, and/or components, functioning together for a specific application, permanently installed and de-installed by professionals at a given place, and used and maintained by professionals in an industrial manufacturing facility or research and development facility;

Compressor packages meant for stationary application would most likely meet this definition (with reservation[38]) and would thus be excluded from the WEEE Directive scope. The indicative list in Annex II does not mention tools generating compressed air.

Compressor packages that are moveable and/or do not require installation by professionals (for example smaller 'plug-and-play' piston packages, as sold in DIY stores) may be covered by the WEEE Directive as they are not 'stationary'.

Category 9 of Annex I mentions 'Other monitoring and control instruments used in industrial installations (e.g. in control panels)'. This could in principle apply to compressor control and monitoring panels. However, Article 2.3.b mentions as exclusion: 'equipment which is specifically designed and installed as part of another type of equipment that is excluded from or does not fall within the scope of this Directive, which can fulfil its function only if it is part of that equipment'.

Therefore control equipment specifically designed for and to be used with large stationary industrial tools, such as compressors, may be exempted (with reservations).

The scrap value of compressors makes it unlikely the equipment does not reach a treatment facility after it's useful life. The materials are not dispersed in the environment and collection is relatively easy.

---

[37] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=URISERV%3Aco0012

[38] 'With reservation' is added as the authors cannot provide a legally binding interpretation of the Directive.

1.3.12 RoHS - Restriction of the Use of Certain Hazardous Substances

The Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast) applies the same scope as the WEEE [39].

The RoHS Directive, in tandem with the WEEE Directive prevents the use of certain hazardous materials in new electrical and electronic equipment (EEE) placed on the market. This limits the impact of the EEE at the end of its life and it also ensures harmonisation of legislation on the use of hazardous materials in EEE across all Member States.

The substances restricted are (maximum concentration values by weight in homogeneous materials):

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominated diphenyl ethers (PBDE) (0,1 %)

Annex III presents a list of 39 exemptions (subgrouping applies) for some equipment where it is understood that one or more these substances is required for their functioning and no economically viable alternatives exist in sufficient quantity at present. Therefore, some of these substances may still be found in some electrical and electronic equipment.

The Annex has been revised on a number of occasions, altering the list of exclusions and limit values.

If, as argued in the section on WEEE, stationary compressors are excluded from the scope one can still expect some 'knock-on' effects' as more and more printed circuit boards are produced without lead or other prohibited substances.

Other hazardous substances, as indicated by environmental organisations

Just for completeness, according a coalition of environmental and health NGO's the following other substances should be regulated under this Directive.[40]

PVC and other chlorinated polymers

Chlorinated polymers such as PVC are commonly present in conjunction with brominated materials, primarily brominated flame retardants. The combination of these two groups of materials can result in emissions of mixed chlorinated-brominated dioxins/furans when combusting, possibly during end of life processing. These chemicals could constitute a significant fraction of the total halogenated dioxin/furan burden from use of such materials, and the mixed chlorinated-brominated dioxins/furans may be as toxic, than the more well-known chlorinated dioxins/furans.

Areas of use of PVC[41]s:

- External cabling and wire
- Internal cabling and wires (including ribbon cables)
- Housing

[39] DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, OJ L 174 of 1 July 2011. Recast of 2002/95/EC.

[40] http://www.greenpeace.org/raw/content/international/assets/binaries/ngo-rohs-submission.pdf

[41] http://www.greenpeace.org/international/Global/international/planet-2/report/2009/1/green-electronics-survey-2.pdf

- Packaging
- Plastic coated/encased electrical connectors
- Home cinema sets, DVD players/ recorders, lighting equipment, PC's.

Brominated flame retardants (BFRs)

The RoHS directive currently allows an exemption for one chemical of the PBDE group, namely deca-BDE. Studies have demonstrated the potential for environmental contamination with persistent, bio accumulative and toxic chemicals that can be produced during the processing of materials containing organic-bound bromine (which include all BFRs), as well as organic-bound chlorine (which includes the plastic PVC). The data from these studies relating to halogenated dioxins/furans (polychlorinated dibenzo-dioxins and –furans), include;

- chlorinated dioxins/furans arising from chlorinated materials (e.g. PVC)
- brominated dioxins/furans from brominated materials (e.g. all BFRs)
- mixed chlorinated-brominated dioxins/furans arising from mixtures of chlorinated and brominated materials (e.g. PVC and BFRs in the same source).

Areas of use of BFRs:

- Laminates of printed wiring boards, including flexible circuit boards.
- Battery, including casing and components
- Housing (including for periphery equipment, e.g. transformer)
- Fan and fan housing
- Ribbon cables
- Electrical insulation sheet
- Plastic coated/encased electrical connectors

Phthalate esters (phthalates)

Subsequent to this submission, studies have been released that demonstrate the widespread use of phthalates in some classes of EEE; laptop computers and mobile phones. These studies demonstrate the use of numerous phthalates, primarily as plasticisers (softeners) in materials manufactured from PVC and other polymers.

Due to concerns over human exposure to toxic and potentially toxic chemicals, the use of certain phthalates is banned in toys and childcare articles.[42]

Areas of use of phthalates:

- Polyvinylchloride (PVC)[43]

Beryllium

Beryllium is primarily used as a hardening agent in alloys, notably beryllium copper. Beryllium, beryllium alloys and beryllium compounds are used in for instance connectors or as a component in heat sink. Beryllium has been used in the past in the form of beryllium copper in connectors of various kinds. Certain manufacturers have phases out the use of Beryllium voluntarily and their products are now beryllium-free.

Antimony

Antimony is mainly used in combination with BFRs to increase fire protective properties. Certain manufacturers have already phased out antimony voluntarily and antimony trioxide is no longer used in any major part. There are also other applications for antimony such as moisture

[42] http://europa.eu/rapid/pressReleasesAction.do?reference=IP/99/829&format=HTML&aged=1&language=EN&guiLanguage=en

[43] http://www.sonyericsson.com/cws/download/1/308/336/1193062465/SE_Environmental_Policy_local.pdf

protection and in varistors. For moisture protection, alternatives have been developed and replacement is well on the way, but for varistors no alternatives have been identified and this use is exempted from the phase-out plan until replacement materials have been identified.

Also Nickel-compounds and Bismuth are considered hazardous by these organisations.

1.3.13 Packaging - Directive on Packaging and Packaging Waste

The Directive 94/62/EC (amended by 2004/12/EC, 2005/20/EC and Regulation No 219/2009) covers all packaging placed on the market in the Community and all packaging waste, whether it is used or released at industrial, commercial, office, shop, service, household or any other level, regardless of the material used.

The EC Packaging Directive seeks to reduce the impact of packaging and packaging waste on the environment by introducing recovery and recycling targets for packaging waste, and by encouraging minimisation and reuse of packaging[44]. A scheme of symbols, currently voluntary, has been prepared through Commission Decision 97/129/EC[45]. These can be used by manufacturers on their packaging so that different materials can be identified to assist end-of-life recycling.

The Commission updates the list of examples given in Annex I to illustrate the definition of the term “packaging”. According Article 1 packaging is either the 'primary packaging' (sales packaging), the 'secondary packaging' (grouped packaging) or the 'tertiary (transport) packaging'.

Member States should take measures to prevent the formation of packaging waste, and to develop packaging reuse systems reducing their impact on the environment. The Member States must introduce systems for the return and/or collection of used packaging to attain the following targets:

a) by no later than 30 June 2001, between 50 and 65% by weight of packaging waste to be recovered or incinerated at waste incineration plants with energy recovery;
b) by no later than 31 December 2008, at least 60% by weight of packaging waste to be recovered or incinerated at waste incineration plants with energy recovery;
c) by no later than 30 June 2001, between 25 and 45% by weight of the totality of packaging materials contained in packaging waste to be recycled (with a minimum of 15% by weight for each packaging material);
d) by no later than 31 December 2008, between 55 and 80% by weight of packaging waste to be recycled;
e) no later than 31 December 2008 the following targets for materials contained in packaging waste must be attained:
    - 60% for glass, paper and board;
    - 50% for metals;
    - 22.5% for plastics and;
    - 15% for wood.

The 2006 Report on the implementation of Directive 94/62/EC on packaging and packaging waste concluded that almost half of the Member States held derogations applying until 2015. Nevertheless, the objectives set for 2008 in Directive 2004/12/EC were to remain valid, even after 2008.

The incineration of waste at plants with energy recovery is regarded as contributing to the realisation of these objectives.

Directive 94/62/EC lays down essential requirements with which these countries should comply regarding the composition and the reusable and recoverable nature of packaging and packaging waste. The Commission is to promote the development of European standards relating to these essential requirements.

[44] OJ L 365 , 31.12.1994 P. 10-23

[45] OJ L 050, 20.02.1997 P. 28 – 31

Member States must ensure that packaging placed on the market complies with the essential requirements of Annex II:

- to limit the weight and volume of packaging to a minimum in order meet the required level of safety, hygiene and acceptability for consumers;
- to reduce the content of hazardous substances and materials in the packaging material and its components;
- to design reusable or recoverable packaging.

Member States should develop information systems (databases) on packaging and packaging waste so that realisation of the targets of this Directive can be monitored. The data they hold must be sent to the Commission in the formats laid down in Annex III.

1.3.14 IED - Industrial Emissions Directive 2010/75/EC

Industrial production processes account for a considerable share of the overall pollution in Europe (for emissions of greenhouse gases and acidifying substances, wastewater emissions and waste). In order to take further steps to reduce emissions from such installations, the Commission adopted its proposal for a Directive on industrial emissions on 21 December 2007. The Industrial Emissions

Directive 2010/75/EC (IED) entered into force on 6 January 2011 and has to be transposed into national legislation by Member States by 7 January 2013.

The Directive on industrial emissions recasts seven existing Directives related to industrial emissions into a single clear and coherent legislative instrument. The recast includes:

- The **IPPC Directive** (Directive 96/61/EC, replaced by Directive 2008/1/EC concerning integrated pollution prevention and control - the IPPC Directive)
- the **Large Combustion Plants Directive** (Directive 2001/80/EC on pollutants emitted by large combustion plants);
- the Waste Incineration Directive (Directive 2000/76/EC on the incineration of waste);
- the Solvents Emissions Directive (Directive 1999/13/EC on volatile organic compounds) and;
- three Directives on Titanium Dioxide (Directives 78/176/EEC, 82/883/EEC and 92/112/EEC on waste and discards from the titanium dioxide industry).

On 7 January 2014, the IED repealed and replaced Directive 2008/1/EC on integrated pollution prevention and control (IPPC), Directive 2000/76/EC on waste incineration, Directive 1999/13/EC on activities using organic solvents and Directives 78/176/EEC, 82/883/EEC and 92/112/EEC, concerning titanium dioxide production. On 1 January 2016, Directive 2001/80/EC on large combustion plants (LCP) was repealed.

This integrated approach to issuing permits to industrial installations should allow major progress to be made in the field of atmospheric pollution. The central element of this approach is the implementation of Best Available Techniques (BAT).

The IED is the successor of the IPPC Directive and in essence, it is about minimising pollution from various industrial sources throughout the European Union. Operators of industrial installations operating activities covered by Annex I of the IED are required to obtain an integrated permit from the authorities in the EU countries. About 50 000 installations were covered by the IPPC Directive and the IED will cover some new activities which could mean the number of installations rising slightly.

The IED is based on several principles, namely (1) an integrated approach, (2) best available techniques, (3) flexibility, (4) inspections and (5) public participation.

1. The integrated approach means that the permits must take into account the whole environmental performance of the plant, covering e.g. emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure. The purpose of the Directive is to ensure a high level of protection of the environment taken as a whole. Should the activity involve the use, production or release of relevant hazardous substances, the IED requires operators to prepare a baseline report before starting an operation of an installation or before a permit is

updated having regard to the possibility of soil and groundwater contamination, ensuring the integrated approach.

2. The permit conditions including emission limit values (ELVs) must be based on the Best Available Techniques (BAT), as defined in the IPPC Directive[46]. BAT conclusions (documents containing information on the emission levels associated with the best available techniques) shall be the reference for setting permit conditions. To assist the licensing authorities and companies to determine BAT, the Commission organises an exchange of information between experts from the EU Member States, industry and environmental organisations. This work is co-ordinated by the European IPPC Bureau of the Institute for Prospective Technology Studies at the EU Joint Research Centre in Seville (Spain). This results in the adoption and publication by the Commission of the BAT conclusions and BAT Reference Documents (the so-called BREFs).
3. The IED contains certain elements of flexibility by allowing the licensing authorities to set less strict emission limit values in specific cases. Such measures are only applicable where an assessment shows that the achievement of emission levels associated with BAT as described in the BAT conclusions would lead to disproportionately higher costs compared to the environmental benefits due to:
   a. geographical location or the local environmental conditions or
   b. the technical characteristics of the installation.

   The competent authority shall always document the reasons for the application of the flexibility measures in the permit including the result of the cost-benefit assessment. Moreover, Chapter III on large combustion plants includes certain flexibility instruments (Transitional National Plan, limited lifetime derogation, etc.)
4. The IED contains mandatory requirements on environmental inspections. Member States shall set up a system of environmental inspections and draw up inspection plans accordingly. The IED requires a site visit shall take place at least every 1 to 3 years, using risk-based criteria.
5. The Directive ensures that the public has a right to participate in the decision-making process, and to be informed of its consequences, by having access to:
   a. permit applications in order to give opinions,
   b. permits,
   c. results of the monitoring of releases and
   d. the European Pollutant Release and Transfer Register (E-PRTR). In E-PRTR, emission data reported by Member States are made accessible in a public register, which is intended to provide environmental information on major industrial activities. E-PRTR has replaced the previous EU-wide pollutant inventory, the so-called European Pollutant Emission Register (EPER).

In addition, through the European Pollutant Release and Transfer Register (E-PRTR). emission data reported by Member States are made accessible in a public register, which is intended to provide environmental information on major industrial activities.

Reviews

Articles 30(9) and 73 of the IED require the Commission to review the need to control emissions from certain types of animal rearing and from the combustion of fuels in certain types of combustion plants and to report the results of those reviews to the European Parliament and the Council. This report was adopted by the Commission on 17 May 2013 (COM(2013) 286 final).

[46] Note that the IPPC definition of BAT may be different to that used in Ecodesign studies, following the MEEuP, MEErP.

1.3.15 Directive (EU) 2015/2193 on medium combustion plants (MCP)

The MCP Directive regulates emissions of sulphur dioxide (SO2), nitrogen oxides (NOx) and dust from the combustion of fuels in plants with a rated thermal input equal to or greater than 1 megawatt (MWth) and less than 50 MWth.

1.4 MS Legislation

No Member State legislation specific for low pressure and/or oil-free compressors at product level has been identified.

1.5 Third country legislation and voluntary initiatives

The search for legislation and measures in third Countries (extra-EU) using the CLASP database on standards and labels[47] produced standards and labels for China, Mexico and USA.

Oddly enough, the EU is missing in the Clasp overview although its legislative procedure for standard air compressor packages was more advanced than that in the USA for a large part of 2015.

1 - China

The current measure in China for mandatory Minimum Energy Performance Standard for compressors of various types, including oil-free piston compressors was introduced in 2009.

Table 16 Overview of Chinese legislation applicable to compressors

Type	**Minimum Energy Performance Standard**
Mandatory/voluntary	**Mandatory**
Most Recent Effective Date	2009
Title	GB 19153-2009 Minimum allowable values of energy efficiency and energy efficiency grades for displacement air compressors
Implementing Organization	NDRC (National Development and Reform Commission) and AQSIQ (General Administration of Quality Supervision, Inspection and Quarantine of China)
International Association	APEC
Scope	The following types of air compressors are covered: Direct drive portable reciprocating piston air compressors, Reciprocating piston micro air compressors, Oil-free reciprocating piston air compressors, Stationary reciprocating piston air compressors for general use, Oil injected screw air compressors for general use, Oil injected single screw air compressors for general use, and Oil flooded sliding vane air compressor for general use.
Test	GB/T 3853-1998
Associated Test Procedure	ISO 1217
Type	Endorsement label
Mandatory/voluntary	**voluntary**
Most Recent Effective Date	2009
Title	GCQC31-432331-2009. CQC Mark Certification - Displacement Air Compressors
Implementing Organization	CQC (China Quality Certification Centre)

[47] http://clasp.ngo/Tools/Tools/SL_Search/SL_SearchResults

International Association	APEC
Scope	Applies to portable reciprocating piston, micro reciprocating piston, oil less lubricating reciprocating piston, general use fixed reciprocating piston, general use oil injected rotary screw, general use oil injected single rotary screw, and general use sliding vane air compressors
Test	GB 19153-2009
Associated Test Procedure	ISO 1217

2 - Mexico

Mexico introduced a voluntary endorsement label in 2012.

Table 17 Overview of Mexican legislation applicable to compressors

Type	**Endorsement Label**
Mandatory/voluntary	Voluntary
Most Recent Effective Date	2012
Title	Sello FIDE No. 4142
Implementing Organization	Fideicomiso para el Ahorro de Energía Eléctrica - FIDE (Trust for Saving Electrical Energy)
International Association	SEAD, APEC
Scope	This endorsement label establishes specifications for screw type air compressors with or without integrated dryer, using AC electric motors from 2.24kW (3HP) to 447.60kW (600HP), with a supply rated voltage of 208-230/460V and a frequency of 60Hz
Test	CAGI/PNEUROP PN2CPTC2
Associated Test Procedure	

3 - USA

DOE issued a framework document in February 2014 initiating a rulemaking[48] to set standards for commercial and industrial air compressors. This document and the subsequent consultation

[48] Normally in the US the word "legislation" refers to acts of Congress (legislature/parliament), whose members are directly elected by the public. It is possible for energy standards to arise that way, but most are issued by DOE, whose leadership is directly appointed by the president of the country. In the DOE case, the resulting standard is normally called a "rule" or "administrative law" to distinguish it from ordinary "law" or "legislation" that comes from congress.

with interested parties and analysis by an external contractor has resulted in a proposed rulemaking, the details of which can be found at:

https://www.regulations.gov/#!docketDetail;D=EERE-2013-BT-STD-0040

And https://energy.gov/sites/prod/files/2016/12/f34/Compressors_Standards_Final_Rule.pdf

The current state (February 2017) is that the **test standard** (see also section 1.2.14) is published in the Federal Register, whereas the efficiency standard isn't. However, the Notice of Final Rule Pertaining to Energy Conservation Standards for Compressors was published on 12 December 2016. The correct reference is 'pre-publication'.

The final ruling is quite different in content from all the text of the draft versions. In the final ruling oil-free and low pressure compressors are excluded as these are too much application-specific machines and represent only very limited savings potential.

The scope of the final "Energy Conservation Standards for Air Compressors" only covers compressors which meet all of the following criteria:

- *Is an air compressor,*
- *Is a rotary compressor,*
- *Is not a liquid ring compressor,*
- *Is driven by a brushless electric motor,*
- *Is a lubricated compressor,*
- *Has a full-load operating pressure greater than or equal to 75 pounds per square inch gauge (psig) and less than or equal to 200 psig*[49]*,*
- *Is not designed and tested to the requirements of The American Petroleum Institute standard 619, "Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries,"*
- *Has full-load actual volume flow rate greater than or equal to 35 cubic feet per minute (cfm), or is distributed in commerce with a compressor motor nominal horsepower greater than or equal to 10 horsepower (hp)*[50]*,*
- *Has a full-load actual volume flow rate less than or equal to 1,250 cfm, or is distributed in commerce with a compressor motor nominal horsepower less than or equal to 200 hp,*[51]
- *Is driven by a three-phase electric motor,*
- *Is manufactured alone or as a component of another piece of equipment; and*
- *Is in one of the equipment classes listed in the Table 1, must have a full-load package isentropic efficiency or part-load package isentropic efficiency that is not less than the appropriate "Minimum Package Isentropic Efficiency" value listed in Table 1 of this section.*

It does not cover oil-free compressors, nor low pressure compressors.

The new energy conservation standards for compressors adopted by DOE are:

Table 18 US DOE Proposed Energy Conservation Standards for Compressors

Equipment class	Minimum package isentropic efficiency	η_{Regr} (package isentropic efficiency reference curve)	'd'
Rotary; Lubricated; Air-	$\eta_{Regr} + (1 - \eta_{Regr}) * (d/100)$	$-0.00928 * \ln(.4719 * V_1)^2 + 0.13911 * \ln(.4719 * V_1) +$	−15

[49] 75 to 200 psig aligns with 5.2 to 13.8 barg.

[50] 35 cfm aligns with 16.5 l/s and 10 hp with 7.5 kW.

[51] 1250 cfm aligns with 590 l/s and 200 hp with 150 kW.

cooled; Fixed-speed		0.27110	
Rotary; Lubricated; Air-cooled; Variable-speed	$\eta_{Regr} + (1 - \eta_{Regr}) * (d/100)$	$-0.01549 * \ln(.4719 * V_1)^2 + 0.21573 * \ln(.4719 * V_1) + 0.00905$	−10
Rotary; Lubricated; Water-cooled; Fixed-speed	$.02349 + \eta_{Regr} + (1 - \eta_{Regr}) * (d/100)$	$-0.00928 * \ln(.4719 * V_1)^2 + 0.13911 * \ln(.4719 * V_1) + 0.27101$	−15
Rotary; Lubricated; Water-cooled; Variable-speed	$.02349 + \eta_{Regr} + (1 - \eta_{Regr}) * (d/100)$	$-0.01549 * \ln(.4719 * V_1)^2 + 0.21573 * \ln(.4719 * V_1) + 0.00905$	−15

Summary

The oldest minimum energy efficiency requirements applicable to compressors within scope are from China. The US has however published a working document (proposed rulemaking) dated 19 May 2016 that presents possible minimum requirements for various compressor categories. The Mexican requirements are just an endorsement label, details of which are unknown.

The following overview shows the scope of the requirements by China, USA and the EU Working Document (presented on 23 Oct 2014).

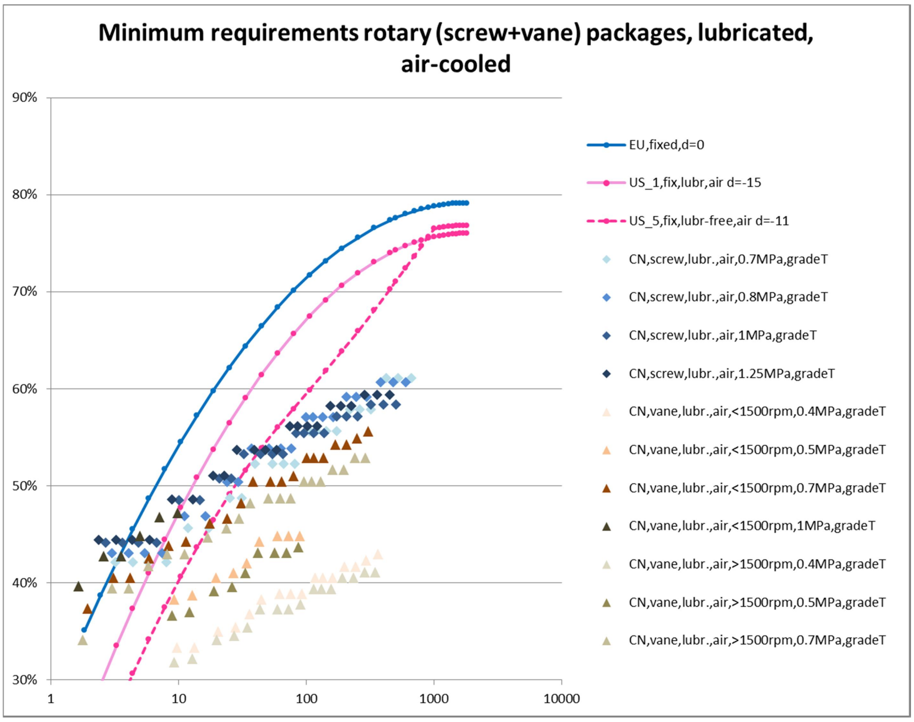
Table 19 Overview of global legislation applicable to compressors

Scope	Jurisdiction		
	China	**USA (proposed rulemaking)**	**EU (standard air only)**
Piston	oil lubricated direct drive portable reciprocating piston air compressors, 0.25-3kW, discharge: 0.25-1.0MPa oil-free direct drive portable reciprocating piston air compressors, 0.25-3kW, discharge: 0.25-1.0MPa reciprocating piston miniature air compressors, 0.18-18.5kW, discharge: 0.25-1.4MPa oil-free reciprocating piston air compressors, 0.18-22kW, discharge: 0.4-1.4MPa stationary reciprocating piston air compressors for general use, 18.5-560kW, discharge: 0.7-1.25MPa water/air lubricated/oil-free	Piston: 1-phase and 3-phase, lubricated only, air/water-cooled but no requirements	Piston: three-phase only, 2-64 l/s, lubricated only, air/water-cooled requirements proposed
Rotary, lubricated	oil injected screw air compressors for general use and oil injected single screw air compressors for general use, 2.2-630kW, discharge: 0.7-1.25MPa water/air	air-cooled requirements	Rotary, lubricated requirements, air/water-cooled
	oil flooded sliding vane air compressors for general use, 1.5–160kW, discharge: 0.4-1.25MPa water/air </> 1500 rpm	water-cooled requirements	

Rotary, lubricant-free	(no requirements)	air-cooled requirements water-cooled requirements	(subject of this study)
Dynamic compressors	(no requirements)	(no requirements)	(subject of this study)

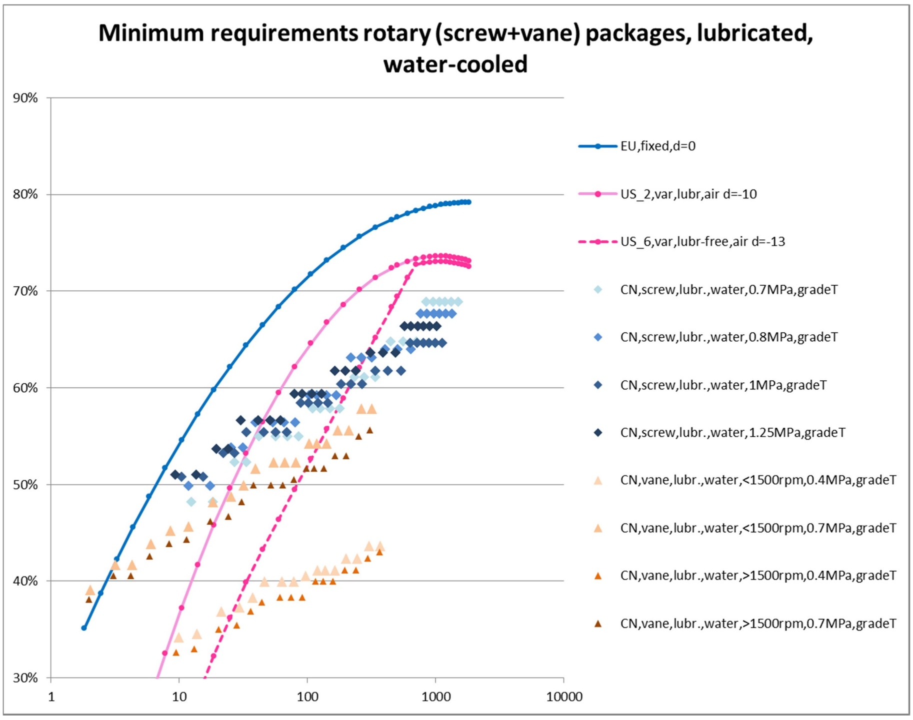
The horizontal x-axis has a logarithmic scale to better show differences at lower volume flows.

Figure 3 Chinese, US and EU (proposed) requirements for rotary (screw, vane), lubricated, air-cooled packages



The figure shows that the EU proposed requirements are more stringent than elsewhere (except for some Chinese requirements on low flow equipment).

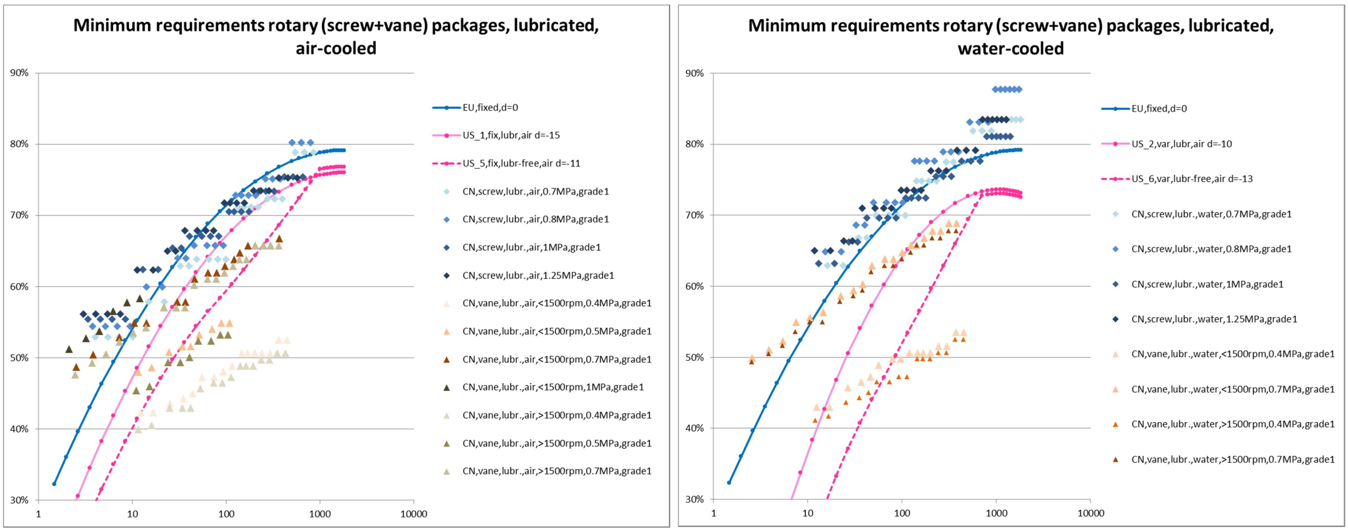
Figure 4 Chinese, US and EU (proposed) requirements for rotary (screw, vane), lubricated, water-cooled packages



Analysis shows that the Chinese "T" requirements (T=target) are close to a D-value[52] of 60, and is not considered to change the market significantly.

However, if the Chinese increase targets to the 1st grade, then it becomes comparable to EU/US requirements. The figures show that US proposed minimum requirements are less stringent than that of the EU.

Figure 5 Chinese, US and EU (proposed) requirements for rotary (screw, vane), lubricated, water-cooled packages – with Chinese requirements set at level "1"



[52] For an explanation of the concept of the "D-value" please see Section 6.2.1.

1.6 Voluntary initiatives

1.6.1 CAGI performance verification program

The CAGI performance verification program is described in the CAGI webpages[53] as follows:

Who can participate?

Participation is voluntary and is open to all manufacturers, whether they are a CAGI member or not, Rotary Compressors from (roughly) 4-150 kW, and standalone Refrigerated Compressed Air Dryers from (roughly) 90-500 l/s.

How is a Participating Manufacturer recognized for participation?

Participating Manufacturers and the results of the verification tests will be posted on this website. Participating Manufacturers that pass the verification program test procedures will be allowed to utilize the CAGI Program Verification Seal on the models' specification sheets and in its product literature. This is the Participant's public representation that the stated Air Flow Capacities and Efficiencies have been verified by an independent laboratory.

What is being verified?

The Program verifies the information that participating Manufacturers publish on the standard CAGI Data Sheets, which are published on the Participants' websites and in their product literature. The Data Sheets define operational and performance information used during the specification and application decision making process.

How does the Independent Verification process work?

On a regular and random basis the administrator will select and test samples of the equipment to verify that they meet the Manufacturers' certified published performance ratings. Two units will be tested annually per participant. The units will be selected at random by the program administrator from manufacturer or distributor available stock. If a tested unit does not pass, the manufacturer has the option to have a second unit, which was previously chosen by the administrator tested. If this unit also fails the manufacturer must re-rate the unit based on the test results within 30 days or be ejected from the Verification program.

What test methods are being used?

- *Compressors - ISO 1217, Displacement Compressors - Acceptance Tests*
- *Air Dryers - ISO 7183, Compressed Air Dryers - Specifications and Testing and Performance Ratings*

CAGI Data sheets

Standard formats for reporting performance have been developed by the members of the rotary positive compressor, air drying & filtration, and lower sections as a service to end users of compressed air system equipment. The participating members of these sections agreed to use the CAGI Datasheets, and post them on their websites.

Sheets are available for:

1. *Refrigerated Compressed Air Dryers*
2. *Rotary Compressor*
3. *Rotary Variable Frequency Drive Compressor*
4. *Centrifugal Compressors*
5. *Blowers*[54]

[53] http://www.cagi.org/performance-verification/overview.aspx

a. *Positive Displacement Fixed Speed Blower - Standard Conditions*
b. *Positive Displacement Variable Speed Blower - Standard Conditions*
c. *Centrifugal Blower - Standard Conditions*

The data sheets specify measuring and reporting of the following performance characteristics for each compressor tested:

- Lubrication type,
- Cooling method,
- Rated capacity at full-load operating pressure,
- Full-load operating pressure,
- Driver motor nominal rating and efficiency
- Fan motor nominal rating and efficiency (if applicable),
- Total package input power at zero flow and at the rated capacity at full-load operating pressure, and
- Specific package input power at rated capacity at full-load operating pressure.

Participating manufacturers will be subject to random testing of two units annually,

which will be compared to certified published performance ratings. Units that do not pass may either be subject to additional testing or re-rated to generate new verified data sheets. Failure may result in ejection from the verification program. For units that pass the verification program test procedures, manufacturers may use the CAGI Verification Seal to advertise that equipment specifications have been tested by an independent laboratory.

The CAGI Performance Verification Program specifies testing at full-load operating pressure for fixed-speed compressors and at a minimum of six test points for variable-speed compressors

according to Annex E of ISO 1217:2009, including:

- maximum volume flow rate;
- three or more volume flow rates evenly spaced between the minimum and maximum volume flow rate;
- minimum volume flow rate; and
- no load power.

Centrifugal blowers are tested using BL300 and reference inlet conditions of p_{amb}=1 bar(a), T_{amb}=20°C, RH=0%. See the CAGI BL 300 Standard.

Manufacturers that participate in the CAGI verification program are: Atlas Copco, BOGE, Chicago Pneumatics, CompAir, FS Curtis, Gardner Denver, Ingersoll Rand, Kaeser, Mattei, Quincy, Sullair, Sullivan Palatek.

Registrations are primarily oil-injected screw, vane and oil-lubricated piston only. Only few manufacturers have registered oil-free screws (Ingersoll Rand, Sullair) or oil-free tooth (Atlas Copco). No other oil-free or typical low pressure equipment has been registered through CAGI (status January 2016).

1.6.2 Compressed air challenge

The Compressed Air Challenge is a voluntary collaboration of industrial users; manufacturers, distributors and their associations; consultants; state research and development agencies;

[54] CAGI offers sheets for option 1 (U.S. customary units) and option 2 (SI units)

energy efficiency organizations; and utilities. This group has the purpose to help users and others involved to enjoy the benefits of improved performance of compressed air systems. [55]

1.6.3 Nordic Swan ecolabel

The Nordic Swan Ecolabel scheme had a criteria document for stationary electric oil-free compressors in which oil-free was defined as: "*The compressor must be designed for oil-free operation (oil-free compression) e.g. no oil or other sealing, lubricating or cooling liquids, except for water, may be present in the compression chamber.*". No further definitions or classifications were included in that document.

The Nordic Ecolabelling Board decided to prolong the validity of the criteria (original publication date 9 October 2003, valid until 9 October 2006) with three years on 10 June 2005 until 10 June 2009. For reasons not disclosed to the authors, the validity of the criteria document was not extended in 2009.

The criteria for compressors and the respective licences were valid until the end of 2011. The criteria development was originally carried out with a fast track method. Nordic Ecolabelling evaluated in 2010 that a revision of criteria would have taken a lot of resources in relation to the market potential for Ecolabelled products. That's why it was decided to not revise the criteria[56].

1.7 Conclusions

Section 1.2 'Test Standards' shows that there are international standards to establish the main (energy) performance parameters. These standards are however mainly technology driven (volumetric or dynamic process) and are currently not providing a common platform for establishing performances that can easily be compared. Standard rating conditions (where defined in the first place) may differ, and calculation methods are not shared (although in principle the performance of each type of compressor can be assessed for a specific working point).

Section 1.3 'EU Legislation' and 1.4 'MS legislation' show that low pressure and oil-free compressors are currently not regulated for environmental aspects within the EU or in a EU Member State.

Section 1.5 'Third country legislation' shows that the USA is currently investigating (possible) rulemaking for compressors, including low pressure and oil-free compressors. China has since 2009 energy performance requirements for various types of 'standard air compressors' including oil-free (piston) compressors.

Section 1.6 'Voluntary Initiatives' shows that increasingly attention is given to establishing performances of (low pressure) compressors of both types (turbo and positive displacement), especially in the context of the CAGI performance verification program (data sheets for blowers and centrifugal equipment).

CAGI also initiated an industry standard for establishing wire-to-air performances of blowers (low pressure compressors) and EU Pneurop has engaged with CAGI to develop a mutual recognised industry standard for this group of compressors. Oil-free compressors operating within 7-15 bar(a) are not (yet) subject to such developments.

Definitions

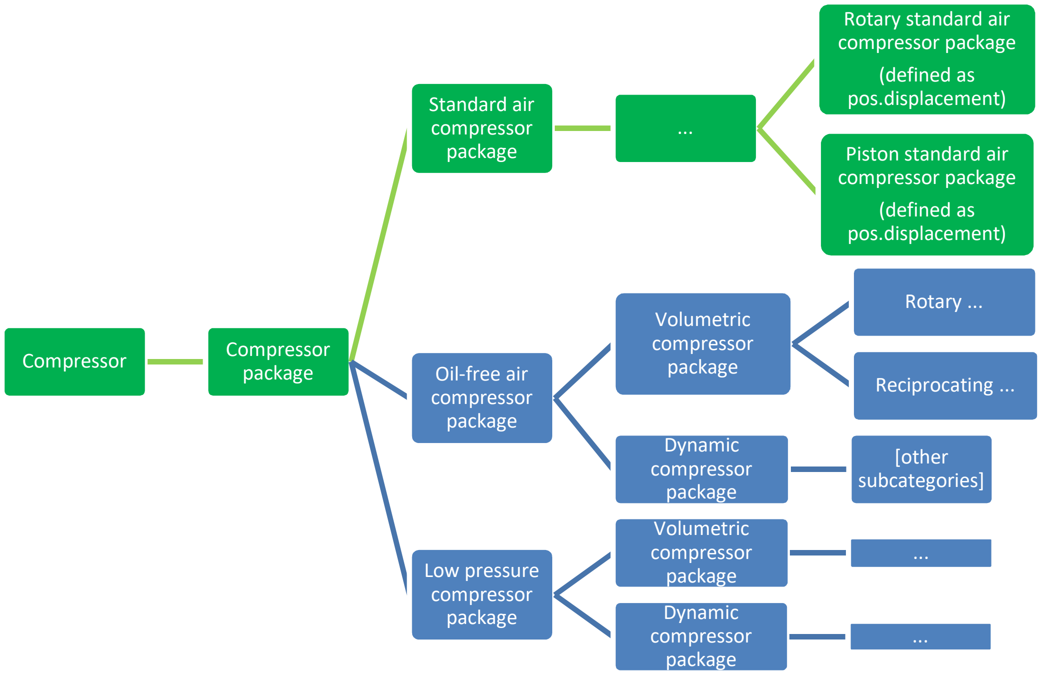
Possible definitions for low pressure and oil-free compressors should be linked to known definitions for compressors as presented in the Commission Working Document discussed in the Consultation Forum meeting of 23 October 2014 on standard air compressor packages.

[55] www.compressedairchallenge.org

[56] Communication from ecolabel.fi, date 29-6-2016

This results in definitions for the compressor, compressor package and a definition for the application range (similar to 'standard air' as in first Lot 31 Working Documents). Subcategories related to technologies could be added if required.

Figure 6 Required definitions for compressor technologies (green=WD 23-10-2014, blue=present report)



The following draft definitions aim to align with TR 12942 descriptions. They cover all technologies. Whether technology specific definitions are actually needed for regulatory purposes cannot yet be answered.

1. 'Compressor' means a machine or apparatus converting different types of energy into the potential energy of gas pressure for displacement and compression of gaseous media to any higher pressure values above atmospheric pressure with a pressure ratio exceeding 1.1;
2. 'Compressor package' means a compressor comprising the compression element ('air end'), prime mover (electric motor), transmission, fully piped and wired internally, including ancillary and auxiliary items of equipment required for safe, continuous and reliable operation; It can include e.g. integrated dryer, compressed air filters;
3. 'Oil-free air compressor package' means a compressor package designed to supply air, at a discharge pressure(s) equal to or higher than 5 bar(a) and not exceeding 15 bar(a), that has been drawn in from the surrounding environment, in which the compressed gas does not come into contact with any lubricant except water;
4. 'Low pressure air compressor package' means a compressor package designed to supply air, at a discharge pressure(s) equal to or higher than 1.1 bar(a) and not exceeding [*to be decided 5 bar(a)*, that has been drawn in from the surrounding environment;

If needed, definitions based on working principles may be added[57]:

1. 'Volumetric(low pressure/oil-free air) compressor package' means a (..) compressor package in which air admission, forced expansion, and diminution of its successive volumes or its forced discharge are performed cyclically by moving members in in a compressor casing;

[57] This is with reservations as a regulatory approach is in principle technology neutral.

[if required, within the group positive displacement, a subdivision into rotary and piston (reciprocating) may be applied]

1.1. 'Rotary (standard air/low pressure/oil-free air) compressor package' means a (..) compressor package in which air admission, forced expansion, and diminution of its successive volumes or its forced discharge are performed cyclically by rotation of one or several rotors in an compressor casing;

1.2. 'Piston (standard air/low pressure/oil-free air) compressor package' means a (..) compressor package in which air admission, forced expansion and diminution of its successive volumes or its forced discharge are performed cyclically by a piston reciprocating in an cylinder;

2. 'Dynamic (low pressure/oil-free air) compressor package' means a (..) compressor package in which the gas pressure increase is achieved in continuous flow essentially by increasing its kinetic energy in the flow path of the machine due to acceleration to high velocities by mechanical action of blades placed on a rapid rotating wheel and further (centrifugal compressor) or gradual (regenerative blowers) transformation of the kinetic energy into the potential energy of the elevated pressure by successive deceleration of the said flow;

[within the group 'Turbo', a subdivision into single stage, and multi-stage may be required]

Other, generic, definitions for various terms:

1. 'Pressure ratio' means the discharge pressure (p_2) divided by the inlet pressure (p_1);
2. 'Discharge pressure' (p_2) means the absolute pressure at the discharge port of the compressor package, expressed in bar(a), and/or as bar(g) ;
3. 'Inlet pressure' (p_1) means the ambient pressure of aspirated air at the inlet, expressed in bar(a);
4. 'Rated maximum volume flow rate' (V_{1max}) means the maximum volume flow of compressed air at rated pressure of the standard air compressor package recalculated to standard inlet conditions, expressed in l/sec;
5. 'Standard inlet conditions' means air is aspirated at an inlet pressure of 100 kPa (1 bar(a)), a temperature of 20°C and a relative water vapour pressure of 0 (zero);

TASK 2: Markets

2 Markets

2.1 Introduction

In this Task 2 a market and economic analysis of low pressure and oil-free compressor packages as placed on the EU market is presented.

2.2 Generic economic data

Eurostat provides data regarding European business statistics of manufactured goods generally referred to as 'Prodcom'. The table on the following page shows the categories that list "compressors" according Prodcom nomenclature year 2014 and the corresponding international Combined Nomenclature (CN).

Two columns have been added that show whether it is "likely", "possibly", "unlikely" that the compressor category is present in the respective application range.

The term "n.a." means 'not applicable' as these compressors are outside the scope of the assignment.

Table 20 Prodcom categories for compressors[58]

PRODCOM	CN	Description	Remarks	Low pressure?	Oil free?
28 13 23 00		Compressors for refrigeration equipment	Refrigeration (cooling and freezing)	n.a.	n.a.
28 13 24 00	8414 40 10 8414 40 90	Air compressors mounted on a wheeled chassis for towing	These are often reciprocating compressors, but screw and vane compressors can also be applied. This category is very diverse as it ranges from small electrically driven piston compressors with two wheels, up to diesel engine driven compressors, to be towed behind vehicles.	n.a.	n.a.
28 13 25 30	8414 80 11	Turbo-compressors, single stage	This group comprises centrifugal compressors as axial compressors are always multi stage. The majority of sales and production covered by this item are probably "turbochargers"[59] (for use in combustion engines) and compressors for braking systems (transport equipment).	likely	likely
28 13 25 50	8414 80 19	Turbo-compressors, multistage	This group can be both centrifugal an axial compressors. As above, part of this category is outside scope if designed for use in 'means of transport'	likely (not axial)	likely
28 13 26 30	8414 80 22	Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow <= 60 m^3/hour	These groups may include mini-compressors used as tyre-repair-kit, a household application inflating toys, balls, air mattresses or other inflatable objects (reciprocating compressors (excluding reciprocating compressor pumps), giving a flow not exceeding 2 cubic metres per minute); according COUNCIL	not likely	likely
28 13 26 50	8414 80 28	… <= 15 bar, > 60 m^3/hr		not likely	likely
28 13 26 70	8414 80 51	… > 15 bar, <= 120 m^3/hr		n.a.	n.a.
28 13 26 90	8414 80 59	… > 15 bar, > 120 m^3/hr		n.a.	n.a.

[58] Source: http://epp.eurostat.ec.europa.eu/newxtweb/submitlayoutselect.do#

[59] Included in "Trade statistics No. 84148011, PRODCOM No. 28132530 - Turbo-compressors, single stage" according to EU Commission EXPLANATORY NOTES TO THE COMBINED NOMENCLATURE OF THE EUROPEAN COMMUNITIES (2008/C 133/01)see also http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2008:133:0001:0402:EN:PDF

			IMPLEMENTING REGULATION (EU) No 1306/2011 of 12 December 2011. (concerning CN codes ex 8414 40 10, ex 8414 80 22, ex 8414 80 28 and ex 8414 80 51) Compressors exceeding 15 bar(a) are obviously outside the scope of study.		
28 13 27 30	8414 80 73	Rotary displacement compressors, single-shaft	Typical rotary compressors with a single shaft are vane, scroll and liquid ring type compressors.	possibly	possibly (scroll)
28 13 27 53	8414 80 75	Multi-shaft screw compressors	These are twin screw compressors, oil-injected and oil-free.	possibly	likely
28 13 27 55	8414 80 78	Multi-shaft compressors (excluding screw compressors)	These are e.g. lobe type compressors and single screw compressors (with two additional gate rotors).	likely	possibly
28 13 28 00	8414 80 80	Air/gas compressors excluding air/vacuum pumps used in refrigeration, air compressors mounted on wheeled chassis, turbo compressors, reciprocating and rotary displacement compressors	According Nomenclature of Trade statistics HS 84148080 this category includes air pumps and ventilating or recycling hoods incorporating a fan, whether or not fitted with filters, with a maximum horizontal side > 120 cm (excl. vacuum pumps, hand- or foot-operated air pumps and compressors). This means that part of this category is outside the scope if they are considered to be 'fans' or other non-compressor equipment[60].	possibly	possibly

2.2.1 EU production and trade in units (2014)

As Prodcom provides information on EU production, extra EU trade, intra EU trade and it allows calculation of apparent consumption (based on production, import, export).

The table below shows data for the year 2014 (unit: pieces). Data for other years (if available) are presented in Annex A.

Table 21 Trade in units, Prodcom 2014 [61]

Prodcom year 2014 (units)	Production	Import to EU	Export from EU	Apparent consumption
28132530 Turbo-compressors, single stage	10.632.361	1.656.120	1.840.836	10.447.645
28132550 Turbo-compressors, multistage	100.000	936.349	178.102	858.247
28132630 Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow <= 60 m³/hour	1.104.598	9.612.420	1.295.462	9.421.556
28132650 Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow per hour > 60 m³	9.870	133.259	15.188	127.941
28132670 Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour <= 120 m³	44.000	277.023	246.614	74.409

[60] see also http://www.zolltarifnummern.de/2012_en/84148080.html

[61] The information was extracted on December 2015 from the Eurostat database "Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data (DS_066341)", Source: http://ec.europa.eu/eurostat/web/prodcom/data/database

28132690 Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour > 120 m³	3.766	113.535	28.931	88.370
28132730 Rotary displacement compressors, single-shaft	140.000	1.782.447	461.878	1.460.569
28132753 Multi-shaft screw compressors	260.000	27.436	190.938	96.498
28132755 Multi-shaft compressors (excluding screw compressors)	30.000	14.519	65.633	-21.114
28132800 Air/gas compressors excluding air/vacuum pumps used in refrigeration, air compressors mounted on wheeled chassis, turbo compressors, reciprocating and rotary displacement compressors	1.792.931	8.982.502	2.175.385	8.600.048
Total	14.117.526	23.535.610	6.498.967	31.154.196

The Prodcom data suggest a total apparent consumption (production + imports - exports) of over 31 million compressor units.

Note that this value includes compressors used for means of transport or for application ranges that are not within the scope of this study and cannot be used to assess the market for low pressure and oil-free compressor packages. No subdivision of data into low pressure and oil free compressors is possible.

The overall and category specific values can therefore not be used for modelling of sales and scope.

The negative value of 'apparent consumption' for category 28132755 Multi-shaft compressors (excluding screw compressors) cannot be explained on the basis of the Eurostat data. The multi-annual production/trade (in units) for this category shows considerable changes in the last 10 years.

Multi-annual analysis

Prodcom allows multi-annual analysis, but given the above comments its usefulness is considered very limited and no conclusions can be drawn on this basis. Nonetheless, this data is provided in Annex A.

2.2.2 EU production and trade in euro (2014)

The apparent EU-2010 market, derived from PRODCOM and Eurostat external trade data, constitutes a value (in msp[62]) of € 5,6 billion.

Table 22 Trade in value, Prodcom 2014 [63]

Prodcom year 2014 (mln euro)	Production	Import to EU	Export from EU	Apparent consumption
28132530 Turbo-compressors, single stage	2.322	392	828	1.885
28132550 Turbo-compressors, multistage	2.200	103	986	1.317
28132630 Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow <= 60	245	206	145	306

[62] Manufacturer selling prices

[63] The information was extracted on December 2015 from the Eurostat database "Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data (DS_066341)", Source: http://ec.europa.eu/eurostat/web/prodcom/data/database

m³/hour				
28132650 Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow per hour > 60 m³	36	19	61	-6
28132670 Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour <= 120 m³	170	9	107	72
28132690 Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour > 120 m³	485	37	221	301
28132730 Rotary displacement compressors, single-shaft	131	52	173	10
28132753 Multi-shaft screw compressors	1.800	17	802	1.014
28132755 Multi-shaft compressors (excluding screw compressors)	207	5	141	71
28132800 Air/gas compressors excluding air/vacuum pumps used in refrigeration, air compressors mounted on wheeled chassis, turbo compressors, reciprocating and rotary displacement compressors	834	332	527	639
Total (million)	8.431	1.171	3.991	5.610

Data for other years (where available) is presented in Annex B.

2.2.3 Parts

Other compressor related Eurostat statistics relate to Prodcom category 28133200 - Parts of air and vacuum pumps, of air and gas compressors, of fans, and of hoods and that are traded as CN8 category: 84149000 - Parts of : air or vacuum pumps, air or other gas compressors, fans and ventilating or recycling hoods incorporating a fan, etc. Prodcom only presents data on the value of this market.

The relevance is limited as data is not limited to air compressors only.

Table 23 Trade in parts, Prodcom 2014

28133200 - Parts of air and vacuum pumps, of air and gas compressors, of fans, and of hoods etc.										
Value (billion euro)	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Production	1,92	2,13	2,5	2,07	1,83	2,18	2,33	2,18	2,07	2,42
Import	0,93	1,1	1,3	1,45	1,14	1,66	1,97	1,96	1,98	1,91
Export	1,61	1,6	2,17	2,07	2,29	2,57	2,53	2,61	2,65	3,04
Apparent consumption	1,25	1,63	1,64	1,45	0,68	1,26	1,77	1,53	1,4	1,29

2.2.4 Installation, repair and maintenance

Eurostat also gives compressor related production statistics on repair and maintenance of pumps and compressors but the relevance of the values remains limited as it comprises compressors **and pumps** of **unidentified types and applications**. Prodcom only presents data on the value of this market.

Table 24 Value of repair & maintenance pumps + compressors (Prodcom 2014)

33121210 Repair and maintenance of pumps and compressors in million Euro																				
Year	Value EU28	BE	BU	CZ	DE	IR	GR	ES	FR	IT	HU	NL	AT	PL	PT	RO	SK	FI	SE	UK
2014	2600		7	55	501		4	142	449	308	16	286	24	84	9	9	31	10	51	494
2013	2460	52	6	48	488		4	145	387	323	20	269	19	71	11	13	21	15	38	494
2012	2380	54	5	46	456		2	149	354	330	25	193	17	118	15	10	31	8	53	510
2011	2360	56	5	48	472		1	130	309	393	15	263	19	53	15	10	23	10	46	472
2010	2296	59	5	42	463		3	121	305	335	4	284	17	49	16	8	31	11	49	472
2009	2235	60	3	39	445	1	4	111	333	427	10	232	15	41	12	20	24	12	44	400
2008	2291	58	6	42	460	6	5	103	403	378	15	238	17	109	9	17	31	15	46	329
2007	1822		8	31	432	1	4	97	187		10	201	16	57	9	11	20	14	68	257
2006	1465		7	24	372	1	4	95	139	209	11	180	16	33	10	11		11	54	217
2005	1483		7	20	353		3	87	141	240	15	130	13	37	11	0		9	48	303
Not shown:																				
Countries with no or limited data: Denmark, Cyprus, Luxembourg, Malta																				
Countries <1.0 million LV, LT, SL, EE																				

2.3 Market and stock data

The data in this section is based on a survey in July 2016, performed by major manufacturers of low pressure and oil-free compressor packages available on the EU market.

2.3.1 Sales

Sales (and power) in base year 2015

In the first Lot 31 study sales for 'standard air' compressor packages were found to be close to 52 thousand reciprocating units and 54 thousand rotary units. The sales of 'low pressure' compressors were estimated to be almost 12 800 units per year and oil-free compressors was 2 000 units per year (applicable to year 2010).

The present study however, based on the 2016 survey by manufacturers of low pressure and oil-free machinery, shows that the sales for low pressure and oil-free compressors as presented in the former Lot 31 study have been underestimated[64].

The 2016 survey resulted in significantly higher sales of 22 497 low pressure units, and 9 335 oil-free units (related to year 2015). The table below shows the overall sales together with the sales of lubricated compressors (from the first Lot 31 study, for year 2015). For 'lubricated / rotary' the share of 'fixed speed' versus 'variable speed' is shown as well.

[64] The initial rough estimation for OF and LP of 2014 was done having in mind a certain product scope, which did not include many small OF and LP compressors, such as side channel compressors, liquid-ring compressors, vane compressors, oil-free piston etc., some of which are sold in relatively large quantities

Table 25 Sales of compressors by technology in EU[65] in 2015

Sales of compressors in EU ('000 units)					
		of which low pressure / oil-free (present Lot 31 study)			
of which 'lubricated' (previous Lot 31 study 2012-2014)		LP: <5 bar(a)	total: 22.5	OF: >5 bar(a)	total: 9.3
reciprocating	52	LP_ZFCR	13.6		
	54 (84%/17%)	LP_ZFCRpeak	5.4	(no data per flow category for OF)	
		LP_LFCR	0.6		
dynamic	(data not captured)	LP_WFCR	2.9		

The sales of the 2016 survey have not been subdivided by technology type by the respondents in order to remain technology neutral. Nonetheless it would be insightful to have some understanding of the size of the market by technology. The below assessment of sales per technology type is mainly based on other, related, studies: the US DOE study of 2016 and a Swiss study.

The US DOE study presented the following assessment of the US market in year 2013.

Table 26 Sales of compressors by technology in USA in 2013 [66]

Sales of compressors in USA ('000 units)[A]	**of which lubricated**	**of which oil-free**	
		LP: <5 bar(a)	OF: >5 bar(a)
reciprocating[B]	539		655[D]
rotary (fix/var)	32 (83%/17%)	1.9[E]	
dynamic[C]	(not applicable)		0.29[F]

Remarks:

A: The US study focused on air compressors within 31 – 225 psig range (approximately 2 to 16 barg);

B: Sales of **reciprocating** compressors in the US appear extraordinary high when compared to the EU sales presented in the first Lot 31 study, which is (at least partially) explained by the inclusion of single-phase compressors in the DOE figures whereas these have been excluded from the EU Lot 31 assessment[67];

C: Sales of dynamic compressors were presented in the DOE webinar of 23 June 2016;

D: Reciprocating sales are presented under "OF: >5 bar(a)" as these are generally not used for low pressure applications;

E: Sales of 'oil-free rotary' comprise equipment > 2 barg and therefore may actually belong to both LP: <5bar(a) and OF: >5bar(a);

[65] VHK calculation, based on Task 2, first Lot 31 study and 2016 market assessment in present Lot 31 study

[66] VHK calculation, based on: DOE Technical support document, page 9-2 (238 of 643).

[67] A possible explanation may be found in oil-free air for dentist practices. There are on average some 70 practising dentists per 100 000 inhabitants in Europe (see reference below) leading to some 300 to 400 000 dentists in Europe. If each practice is equipped with an oil-free compressor (usually a piston or scroll type), with a lifetime of some 8 hrs, the annual sales shall be in the range of some 40 to 50 000 units per year. It may be that most of these units are single phase, 230 V, and outside the scope of this study. If sales of 'hobby' compressors are added, the misalignment between the US and EU study reduces further.

(Source: http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Practising_dentists, _pharmacists_and_physiotherapists,_2013_Health2015B.png)

F: Sales of dynamic machines have been allocated to "OF: >5bar(a)" as dynamic machines in low pressure applications (<5bar(a)) are usually below 2 bar(g) which is outside the scope of the USA assessment and thus not covered.

Another compressor market study was performed in Switzerland in 1998. This study also applied a scope of outlet pressure of 2 to 15 bar(g) – comparable to the US scope. The study presented data for three categories: Lubricated rotary, Lubricated reciprocating and 'Oil-free'. Dynamic compressors have not been assessed separately, but it can be assumed these are present in the category 'oil-free'.

Table 27 Sales of compressors by technology in Switzerland in 1998 [68]

Sales of compressors in Switzerland ('000 units)[A]	**of which 'lubricated'** [A]	**of which 'oil-free'**	
		LP: <5 bar(a)	OF: >5 bar(a)
reciprocating	1.2	0.16	
rotary	1.1		
dynamic	(not applicable)		

Remarks:
A: "Reciprocating' and 'Rotary' are assumed to be 'lubricated' as otherwise they would be covered under "oil-free'.

The above two market assessments have been used to scale the EU market sales (values as 'thousand units') by technology type (rotary, reciprocating or dynamic) and flow control category (wide, limited and zero flow control), where:

LP_ means low pressure application range;
OF_ means oil-free application range;
..**ZFCR** means zero flow control range;
..**LFCR** means limited flow control range;
..**WFCR** means wide flow control range;
..**ZFCRp** means zero flow control range with peak pressure capability;
..|A means air cooled;
..|W means water cooled.

(for further clarification, see Section 4.7)

Oil-free application range

- Various assessments, including the Lot 30 reports (on electric motors), the first Lot 31 study on 'standard air' compressors, the DOE study and the LP assessment, show that the average size of the market with capacity control is close to 20% of the total market. Applied to the OF range this means the OF_ZFCR market is some 7.5 thousand units. The OF_LFCR and OF_WFCR are respectively 16% and 84% of the capacity controlled market, respectively sales of 0.3 and 1.6 thousand units.
- The EU 'lubricated rotary' market is almost 1,7 times the size of the USA 'lubricated rotary' market (54 thousand versus 32 thousand units). The ratio of 'fixed speed' versus 'variable' is also almost identical. Because of this similarity the size of the EU 'dynamic' market has been scaled by 1.7 on the basis of 0.3 thousand 'dynamic' units in the US (units supplying more than 2 bar(g)) leading to 0.5 thousand units of 'dynamic' compressors in the EU (these have been placed in the OF group of >5 bar(a) as the dynamic compressors in the low pressure segment rarely exceed 2 bar(g)). Of these 0.5 thousand units, 0.3 thousand is attributed to the OF_LFCR category, leaving 0.2 thousand units for the OF_WFCR (dynamic equipment is not assumed to be present in the OF_ZFCR category as some form of intentional volume flow control is preferred for OF (pressure > 5 bar) turbo's).

[68] VHK calculation, based on information retrieved from: http://www.energie.ch/themen/industrie/druckluft

- By scaling the US 'oil-free rotary' market of 1.9 thousand units by the same 1.7 factor the EU sales of oil-free rotary equipment become 3.2 thousand units (actually the US market covers equipment >2 bar(g), but here 100% is allocated to >5bar(a)). This may introduce a slight overlap (as in this present study >2 bar(g) to 5 bar(a) is considered "low pressure") but this is considered acceptable. The OF rotary equipment is attributed to categories ZFCR and WFCR (LFCR is already complete with dynamic machines), the relative size depending on assumptions regarding the overall size of the ZFCR category.
- The sales of 'lubricated reciprocating' compressors are not based on the USA study as the first Lot 31 study and the Swiss study both show that sales of lubricated reciprocating machinery is much smaller than the US study shows (lubricated reciprocating versus lubricated rotary gives a factor 1.1 – 1.2 in EU/Switzerland). As the total sales in the EU OF segment cannot exceed 9.3 thousand units, the reciprocating sales in the EU (3 phase only) must be approximately (9.3 – 0.5 – 3.2=) 5.6 thousand units – see above.
- The OF reciprocating sales have been attributed for 80% to the ZFCR range (simple, low power on/off products) which is 4.5 thousand units, and the remaining 20% in the WFCR range (staged or variable capacity products), which is 1.1 thousand units. As stated above, the OF_LFCR range is wholly attributed to dynamic compressors (sales 0.3 thousand units), and the remaining 0.24 thousand units dynamic sales are in the WFCR range. The remaining sales are completed by rotary equipment (3 thousand to OF_ZFCR and 0.2 thousand to OF_WFCR).

Low pressure application range

- The USA and Swiss study are of little use for scaling the EU low pressure (< 5 bar(a)) market as both the USA and Swiss study scope is limited to equipment providing minimum 2 bar(g)/3 bar(a), which overlaps with only a small share of rotary compressors in the 3-5 bar(a) range. It can be expected however that the share of reciprocating compressors in the low pressure range is insignificant (if not zero). EU low pressure sales are therefore either rotary (screw, roots, etc.) or dynamic (side channel, turbo, etc.).
- The authors have not received information on the size of the 'rotary' or 'dynamic' EU low pressure market by technology, but expert judgement indicates a relatively high share of side channel blowers (mainly low power products). If it is assumed that the 5.4 thousand sales in the LP_ZFCRpeak range are 'rotary' (for the pneumatic conveying market segment), and the LP_LFCR sales are (again, as in OF) dynamic compressors only (probably mainly waste water treatment) and the 2.9 thousand unit sales of LP_WFCR range are for 1/3 dynamic (this market segment is growing fast), this leaves only the dynamic sales for the LP_ZFCR range to be estimated in order to complete the picture.
- If the 'dynamic' sales in the LP_ZFCR range are estimated to be 10 thousand units (this is the approximate difference between the first LP sales estimate of 2014, and the present survey result – the difference is believed to be mainly low power regenerative blowers etc.) this leaves 3.6 thousand units for 'rotary'. The overall sales then become 11 thousand units for 'rotary' and 11.5 thousand for 'dynamic' equipment. The average power was provided by the survey.

Combining the above scaling and estimations results in an EU market of compressors as shown below (indicative for year 2015). Added in the overview is the average power, which for the LP categories is an outcome of the manufacturer survey, and for OF categories is the result of an assessment of sales and power which arriving at the same overall sales, power and energy consumption as identified in the survey.

Table 28 EU market (source: VHK and manufacturer survey)

Sales of LP compressors in EU ('000 units)	**LP_all**	**LP_ZFCR**	**LP_ZFCRp**	**LP_LFCR**	**LP_WFCR**
Sales	22.5	13.6	5.4	0.6	2.9
of which recip	*0*	*0*	*0*	*0*	*0*
of which rotary	*11*	*3.6*	*5.4*	*0*	*1.9*

of which dynamic	*11.5*	*10*	*0*	*0.6*	*1*
Average power [kW]	16.5	8.9	23.5	58.4	29.4

Sales of OF compressors in EU ('000 units)	**OF_all**	**OF _ZFCR**	**OF _LFCR**	**OF_WFCR**
Sales	9.3	*7.5*	*0.3*	*1.6*
of which recip	*5.6*	*4.5*	*0*	*1.1*
of which rotary	*3.2*	*3.0*	*0*	*0.2*
of which dynamic	*0.5*	*0*	*0.3*	*0.24*
Avg. power	37.3	*21.1*	*185*	*76*

Values which are *italic* means source is VHK.

The survey did not present sales data for oil-free air- or water-cooled products but the industry did provide energy savings data for these subcategories (see Task 4). In order to allow an assessment of possible measures for also the subcategories air- and water-cooled, an estimate of average power and sales was performed.

VHK assumed that the chance of a product being water-cooled is related to the power consumption. For the purpose of splitting OF_WFCR and OF_ZFCR sales into air- and water-cooled equipment, VHK assumed a sales distribution that differs for the categories, as it is calculated that the ZFCR category representative power is 21 kW and that of the WFCR range is 76 kW.

Figure 7 Sales share of air- vs. water-cooled equipment , for the ZFCR category (x-axis: kW)

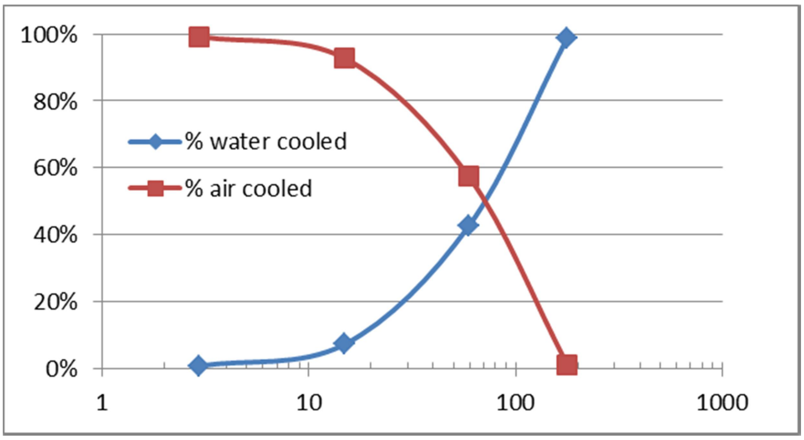
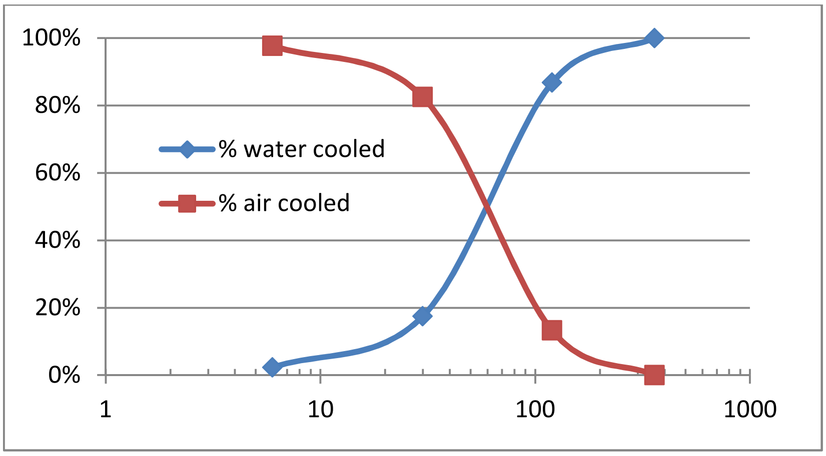


Figure 8 Sales share of air- vs. water-cooled equipment , for the L/WFCR category (x-axis: kW)



VHK then calculated the following sales share (and average power per subcategory):

Table 29 Sales and power for air- or water-cooled OF_WFCR and OF_ZFCR

By main category			By subcategory		
	Sales (pieces)	**Power (kW)**		**Sales (pieces)**	**Power (kW)**
OF_WFCR	1568	76	**OF_WFCR|A**	573	162
			OF_WFCR|W	995	26
OF_ZFCR	7468	21.1	**OF_ZFCR|A**	841	80.4
			OF_ZFCR|W	6552	13.7

Sales 1990-2050

The 2016 survey did not return sales data for historic or projected years. As the historic and projected sales in the first lot 31 study on standard air were based on the GDP development in the EU, the sales for LP and OF equipment have been modelled/projected on the basis of GDP as well.

Based on recent Eurostat data[69] and other sources[70] for projections of GDP (which is an update of the former Lot 31 GDP data), a sales factor for correcting 2015 sales to other years has been calculated by VHK.

Although it is to be expected that not each flow control category has followed / will follow this GDP-derived sales factor exactly, it is considered the best approach available when lacking actual historic sales data and/or industry sales roadmaps.

[69] http://ec.europa.eu/eurostat/statistics-explained/index.php/File:GDP_at_current_market_prices,_2003%E2%80%9304_and_2012%E2%80%9314_YB15.png

[70] https://knoema.com/iuacek/euro-area-gdp-growth-forecast-2015-2020-and-up-to-2060-data-and-charts

Table 30 Sales index based on GDP 1950 to 2015

GDP	1950	1960	1970	1980	1990	2000	2010	2020	2030	2040	2050	Source
GDP change (in % change)							2.07	1.89	1.84	1.51	1.39	A
GDP index (base 2010)	9.8	24.35	38.85	53.45	69.8	87.2	100					B
Sales index, based on A and B source (base2010)	0.24	0.24	0.39	0.53	0.70	0.87	1.00	1.142	1.313	1.462	1.591	C
Sales index (base 2015)	0.23	0.23	0.37	0.51	0.66	0.83	0.95	1.08	1.25	1.39	1.51	D

Remark on Source:

A: https://knoema.com/iuacek/euro-area-gdp-growth-forecast-2015-2020-and-up-to-2060-data-and-charts
B: Eurostat "GDP and main components (output, expenditure and income)" [nama_10_gdp]. Before 2010 is avg. UK-FR, before 1975 is linear trend.
C: Calculated by VHK (from 2018 onwards: OECD corrected by 0.9 to align to 2017-2018 - see source material)
D: Calculated by VHK

This correction factor has been applied to the overall combined "load" of equipment sold, where load was calculated as isentropic power times operating hours, load factor correction and sales in a reference year (2015).

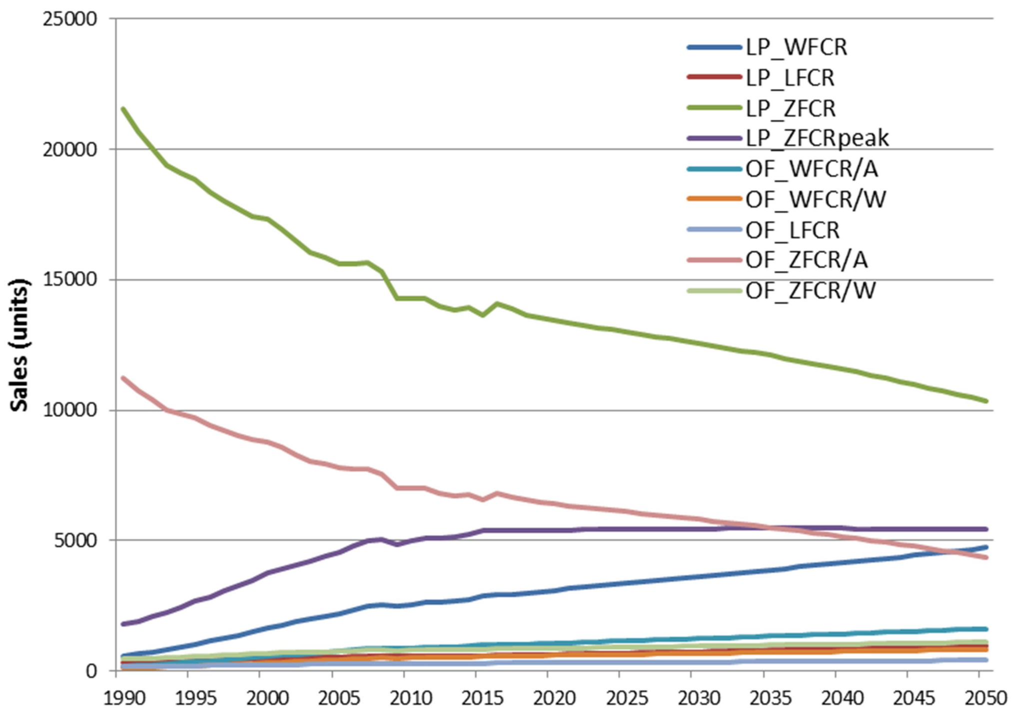
A correction has been applied to sales of LFCR and WFCR categories as VSD's, typically used by rotary equipment allowing intentional flow control, were not widely available before 1995. The correction corrects the 2015 base data so that sales of the WFCR and LFCR categories are nearing zero in year 1995 and before (as there were virtually no VSD's sold in/before that year). Sales have not been corrected to absolutely zero as also other forms of flow control did exist before 1995 (modulation, etc.).

The resulting sales are shown below.

Table 31 Sales of LP and OF equipment

SALES, in 000 units	1990	2000	2010	2020	2030	2040	2050
LP_WFCR	591	1654	2559	2888	3101	3618	4156
LP_LFCR	331	480	562	593	640	743	853
LP_ZFCR	21531	17317	14294	13638	13448	12566	11569
LP_ZFCRpeak	1782	3747	4991	5378	5403	5459	5463
OF_WFCR/air	204	570	882	995	1068	1247	1432
OF_WFCR/water	117	328	508	573	602	677	752
OF_LFCR	167	242	283	299	314	346	379
OF_ZFCR/air	11245	8787	7015	6552	6408	5810	5154
OF_ZFCR/water	469	681	798	841	878	954	1033
LP_all	**24235**	**23198**	**22407**	**22497**	**22592**	**22387**	**22041**
OF_all	**12202**	**10607**	**9486**	**9260**	**9270**	**9034**	**8749**
Total	36437	33805	31893	31757	31862	31421	30791

Figure 9 Sales ('000) for LP and OF flow categories for 1990-2050



Note: the fluctuations between 2007-2015 are due to the economic crisis during that period.

The sales growth rate is derived from the above presented sales.

Table 32 Sales growth rate (over multi-annual periods)

Sales growth rate (% over period)	1990-2015	2015-2030	2030-2050
LP_WFCR	7%	2%	2%
LP_LFCR	2%	2%	2%
LP_ZFCR	-2%	0%	-1%
LP_ZFCRpeak	5%	1%	0%
OF_WFCR/air	7%	2%	2%
OF_WFCR/water	7%	2%	1%
OF_LFCR	2%	2%	1%
OF_ZFCR/air	-2%	0%	-1%
OF_ZFCR/water	2%	2%	1%
LP all	0%	1%	0%
OF all	-1%	1%	0%

The replacement sales for a given year have been calculated as sales in the year the product was placed on the market a product life ago[71].

[71] See Task 2, section 2.3.2 on average product life

Table 33 Replacement sales

Replacement sales (pieces)	1990	2000	2010	2020	2030	2040	2050
LP_WFCR	60	415	1304	2395	2912	3683	4449
LP_LFCR	93	224	338	439	489	612	739
LP_ZFCR	13326	12353	10150	8627	8688	8668	8238
LP_ZFCRpeak	186	929	2318	3767	4150	4546	4802
OF_WFCR/air	16	118	407	801	970	1235	1499
OF_WFCR/water	2	25	129	327	462	577	689
OF_LFCR	11	40	79	113	128	152	179
OF_ZFCR/air	4895	4480	3450	2737	2620	2551	2376
OF_ZFCR/water	4	10	18	24	27	32	36
LP_all	13665	13921	14110	15229	16238	17508	18228
OF_all	4928	4674	4082	4002	4207	4546	4779
Total	18593	18595	18191	19231	20444	22055	23008

The number of replacement sales expressed as share of total sales. The low number for OF_ZFCR|water replacement sales share indicates that the market is growing faster than other markets.

Table 34 Replacement sales as % of total sales

Replacement as % total sales	1990	2000	2010	2020	2030	2040	2050
LP_WFCR	10%	25%	51%	77%	78%	80%	81%
LP_LFCR	28%	47%	60%	69%	64%	65%	65%
LP_ZFCR	62%	71%	71%	64%	65%	66%	68%
LP_ZFCRpeak	10%	25%	46%	70%	75%	75%	76%
OF_WFCR/air	8%	21%	46%	75%	77%	78%	79%
OF_WFCR/water	2%	8%	25%	54%	68%	72%	73%
OF_LFCR	7%	17%	28%	36%	37%	38%	38%
OF_ZFCR/air	44%	51%	49%	43%	43%	44%	47%
OF_ZFCR/water	1%	2%	2%	3%	3%	3%	3%
LP_all	56%	60%	63%	67%	69%	71%	73%
OF_all	40%	44%	43%	43%	45%	47%	49%
Total	51%	55%	57%	60%	63%	64%	66%

The sales of new products (total sales – replacement sales) is:

Table 35 New sales

NEW sales	1990	2000	2010	2020	2030	2040	2050
LP_WFCR	531	1239	1255	705	793	837	910
LP_LFCR	237	255	224	201	269	302	337
LP_ZFCR	8205	4964	4144	4820	4394	3937	3354
LP_ZFCRpeak	1597	2818	2674	1636	1375	1339	1283
OF_WFCR/air	188	452	475	267	291	311	338

OF_WFCR/water	115	303	379	275	215	209	223
OF_LFCR	155	202	204	201	218	236	257
OF_ZFCR/air	6350	4307	3566	3672	3289	2869	2335
OF_ZFCR/water	466	671	780	853	928	1004	1081
LP_all	10570	9277	8297	7363	6830	6414	5883
OF_all	7274	5933	5404	5269	4941	4630	4234
Total	17844	15210	13702	12632	11772	11045	10117

Design cycle

The typical design cycle for **standard air** compressors (the period a model is present in manufacturer catalogues, before it is replaced with a newer model) is some 5 years, meaning that on average some 20% of models is redesigned each year[72]. This is assumed to apply to the **low pressure** range as well.

For **oil-free** compressors it is assumed that the design cycles are longer: The number of companies involved is much smaller than for standard air, and the technologies involved are more R&D intensive, requiring more resources. A design cycle of 10 years is assumed (10% overhaul per year).

For centrifugal turbo compressors in particular the concept of a design cycle is a bit odd, as the majority of products are made specifically for their application: There are virtually no identical centrifugal turbo compressors on the market (at least not below say 75-100 kW).

2.3.2 Product life

In the first Lot 31 study the life of the 'low pressure' compressors was estimated to be 15 years and that of oil-free equipment 20 years. This present study corrects these figures as equipment is generally of much lower power than anticipated in 2012.

The 2016 survey resulted in estimates for product life of low pressure compressors, with an overall average of 10.4 years, ranging from almost 9 years for the zero flow category, to over 13 years for the limited flow category. For oil-free the 2016 survey did not result in data per flow category: Overall life was 12.7 years.

The product life for OF equipment was based on confidential manufacturer data allowing establishing a relation of average product life in relation to power input.

Equation 6 Estimating product life (years) of OF equipment by power (kW)

Product life (years) = 7.25*Power^0.18

Combined with the sales identified for OF this results in an identical sales weighted average product life of 12.7 years.

The standard deviation[73] of compressor life per group depends on the variation of products within the group assessed. Products can differ in technology and size, all influencing standard deviation of product life. The standard deviation for a category would thus reflect the diversity in technologies and sizes. When narrowing down on similar technology and size, the standard deviation reduces (to zero if all equipment is rated as having the same product life).

The standard deviation is therefore rated as <1 for products of same technology and size, and exceeds 6 years for heterogeneous categories.

---

[72] Source: Based on comments made by Pneurop before and during the 23-10-2014 Consultation Forum on standard air compressors.

[73] A discussion of this element, standard deviation, is requested in accordance with the MEErP 2013, the method structuring this study.

2.3.3 Stock / installed base

Assuming that product life will not change / hasn't changed significantly in the period 1990-2050 the stock of installed units in the EU28 is calculated to be as follows:

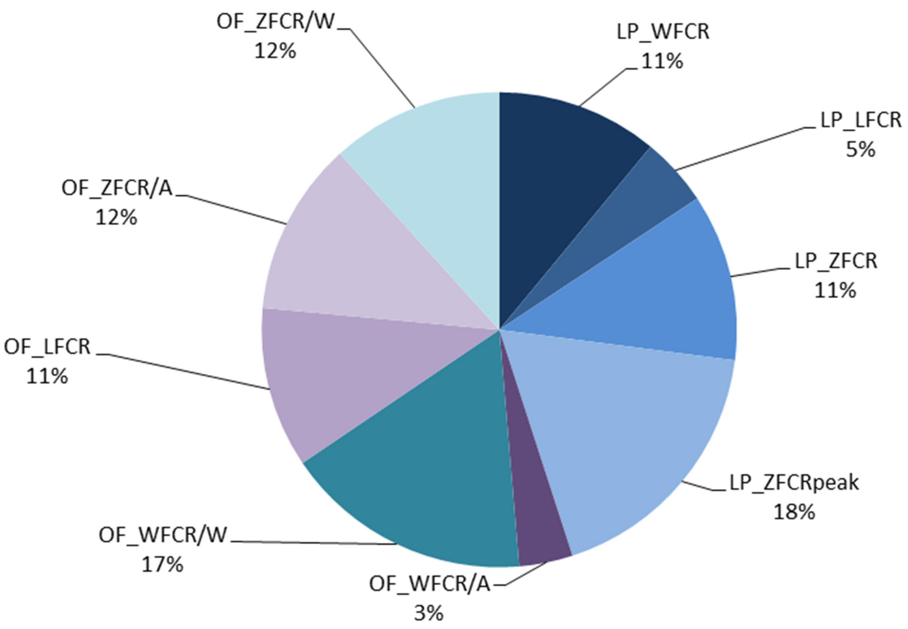
Table 36 Calculated stock and product life

STOCK (000 units)	Product life (year)	Avg. power [kW]	1990	2000	2010	2020	2030	2040	2050
LP_WFCR	12.1	29.4	3	12	26	34	40	46	53
LP_LFCR	12.2	58.4	3	5	6	7	8	10	11
LP_ZFCR	8.4	8.9	182	154	129	115	108	100	91
LP_ZFCRpeak	13.2	23.5	12	33	57	69	72	72	72
OF_WFCR/air	13.1	26.3	1	4	9	13	15	17	20
OF_WFCR/water	18.1	162.3	1	3	6	9	11	12	14
OF_LFCR	18.6	185.0	2	3	4	5	6	6	7
OF_ZFCR/air	11.6	13.7	136	114	92	78	71	64	56
OF_ZFCR/water	16.0	80.4	4	8	11	13	14	16	17
LP_all	10.1	16.5	199	204	218	225	228	229	227
OF_all	12.7		***51***	***65***	***92***	***116***	***136***	***154***	***170***
Total			181	232	318	381	443	502	553

The total installed power (the stock multiplied by the average power, as visualized in the figure below) shows that the low pressure equipment is responsible for almost half (48%) of the installed power (the largest group being ZFCRpeak, with 19% of total LP+OF, which is mainly used in pneumatic conveying).

In oil-free the largest installed power is found in the wide flow control range/water-cooled (17% of total LP+OF). A specific or typical application could not be given (is used in pharmaceutical, food & beverages, automotive/spraying, electronics, etc.).

Figure 10 Installed power (MW) per flow category, for year 2020



2.4 Market structure and trends

2.4.1 Manufacturers

As the technologies for producing low pressure and/or oil-free air are very diverse, so are the manufacturers. But the market has seen progressive consolidation over the years, with smaller manufacturers specialised in a certain technology, being bought by larger groups.

When looking at the oil-free segment in particular, design, engineering and manufacturing of 7-15 bar(a) oil-free screw technology is mastered by a handful companies (the most well-known being Atlas Copco, Ingersoll Rand, Hitachi and Kobelco). Most other suppliers source their oil-free screw air ends from one of these suppliers.

The design, engineering and manufacturing of especially high speed centrifugal compressors, such as applied in low –pressure applications, is also mastered by few companies, but more companies are entering this growing market segment.

This means that a limited number of companies are competing at R&D level in these market segments, which helps to explain the sensitivities regarding manufacturers to publish performance data, prices and market shares.

The paragraphs below presents a (non-complete) overview of major manufacturers of compressor packages per technology. In addition to the below companies there may be some more air-end only manufacturers.

Positive displacement / screw compressors (oil-free)

Oil-free screw compressors are on offer by:

- Atlas Copco;
- Ingersoll Rand;
- Hitachi America, Ltd.;

- Kobelco, Japan.
- Otto Boge GmbH & Co. KG
- Compair UK (Gardner Denver Group),
- Gardner Denver;
- Kaeser;

The largest (in number of air ends produced and sold) manufacturers of oil-free screw compressor air-ends are Atlas Copco, Ingersoll Rand, Kobelco and Hitachi, with the latter two being active in Asia mainly (no real presence in EU market). Boge, Kaeser, Compair, TECA (= Ingersoll Rand) and Sullair are known to use OEM oil-free screw air ends.

Water-injected screw compressors are produced by (alphabetically) ALMIG, Aerzen, Atlas Copco, Bauer, Gardner Denver, among others.

Positive displacement / Reciprocating

Manufacturers of oil-free reciprocating compressors within the intended discharge pressure range are (alphabetically) ALMIG, Atlas Copco, Boge, Howden and KAESER.

Large oil-free reciprocating compressors are typically found in process-gas applications, and here a large group of specialised manufacturers offer reciprocating compressors for these higher pressure ranges, from 15 bar up to 3000 bar.

Positive displacement / Rotary lobe

Oil-free rotary lobe compressors are manufactured by (alphabetically / list not exhaustive) Aerzener Maschinenfabrik, Dresser Rand, Garo S.P.A., Howden Compressors Ltd., KAESER, MAN Diesel & Turbo SE, Pedro Gil S.A., Robuschi (Gardner Denver group)

Beyond the discharge pressure range are products offered by Kobelco Compressors America Inc., Leobersdorfer Maschinenfabrik (helical lobe), VPT Kompressoren GmbH, etc.

Positive displacement/Blade compressors

Blade compressors are designed by Lontra and are expected to appear on the market in the very near future.

Positive displacement/Liquid ring

Liquid ring compressors are on offer by Elmo-Rietschle, Tuthill, SIHI pumps, Nash (Gardner Denver group), Robuschi (Gardner Denver group).

Positive displacement / vane compressors

Vane compressors are on offer by Elmo-Rietschle (Gardner Denver group), Becker, Emmecom, Mils.

Positive displacement / Claw or Tooth compressors

Claw compressors are on offer by Atlas Copco, Busch, Elmo-Rietschle (Gardner Denver group).

Turbo compressors / Centrifugal

Centrifugal compressors may be used in both the low pressure application range and the oil-free application range.

Centrifugal equipment supplying between 1-15 bar, at 42 – 25 000 m^3/min) are on offer by:

- Aerzen;
- Atlas Copco;
- Boge;
- Centac, Cameron (Ingersoll Rand Group);

- Comoti;
- Continental;
- FS-Elliott Co. LLC;
- Howden Compressors Ltd.;
- Ingersoll Rand;
- MAN Diesel & Turbo SE;
- Mitsui Engineering & Shipbuilding;
- Pillaerator
- Samsung Techwin;
- Siemens AG Power And Gas Division
- Sulzer (merged with MAN Germany since 2000)
- Tamturbo.

The integrally geared type is on offer by only a few manufacturers, the direct driven low pressure turbos are produced by more manufacturers.

Turbo compressors / Regenerative blowers

Regenerative (side channel) blowers are on offer by:

- Becker pumps;
- Elektror airsystems;
- Elmo Rietschle (Gardner Denver group);
- Spencer (trade name Vortex);
- Pentair;
- Grainger;
- Greenco;
- Zepher UK;
- Hitachi, Japan.
- GAST;
- Ametek;
- National turbine corporation;
- Hartzell fan Inc.;
- Tuthill vacuum & blower systems;
- Ebm-papst;
- Peerless blowers;
- FPZ.

Turbo compressors / axial

Axial turbo compressors are not a straightforward choice for non-process gas applications, such as low pressure air or oil-free air. This is also the conclusion of Task 3 'Users' and Task 4 'Technologies'. Nonetheless a limited number of manufacturers is shown:

- Elliott Group (max 5 bar, 25 thousand m3/min);

- FS-Elliott Co. LLC (max 5 bar);
- MAN Diesel & Turbo SE, Germany (max 15 bar, 25 000 m^3/min);
- Siemens AG Power And Gas Division STC-SX (max 7 bar, 22 000 m^3/min)
- Comoti, MA series (max 10 bar, 9200 m^3/min);

Size of manufacturers

Most manufacturers can be considered 'large' enterprises (more than 250 employees, over 50 million EUR turnover). The following information is compiled using public sources. It may be amended/extended when more information becomes available.

Table 37 General information of main manufacturers[74]

Name (alphabetically)	Turnover / revenue (EUR)	Employees	Facilities	Ratio (turnover/ employee)	Comments	SME	HQ
Aerzen	300 million	some 2 thousand		150.000 (approximate value)		No	EU/DE
Atlas Copco	8 400 million	some 33 thousand	Belgium, Germany, USA, China and India	254.545	Founded 1873, Sweden	No	EU/SV
Bauer Kompressoren	140 million						EU/DE
Boge	90 million	some 0,5 thousand	Germany (Bielefeld), China (Shanghai)	163.636	Founded 1907, Germany	No	EU/DE
Compair			USA (production in DE, China, USA)				USA
Gardner-Denver, incl. Elmo Rietschle, Robuschi, Champion, Compair, etc.	> 650 million (28% of 2.4 billion)	some 7 thousand	global	92.857	Founded 1859 USA.	No	USA
Howden	73 million	some 4 thousand globally	39 locations globally			No	USA
Ingersoll Rand	16% of revenue made in EU, 66% in USA		over 100 facilities globally		Founded 1871 USA	No	USA
Kaeser Kompressoren	600 million	some 4 thousand		150.000	Founded 1919, Germany	No	EU/DE

[74] Data from 2012. Source: First Lot 31 study, task 2. Compiled by VHK on basis of annual reports of companies, as found on company websites, and various other public sources and updated where data was available.

Siemens	73 000 million	No	EU/DE
(tbc) = to be calculated			

The assessment of whether a company is an SME or larger company, is based on the criteria according EU Recommendation 2003/361.

Table 38 Definition of SME's

Company category	Employees	Turnover	Balance sheet total
Medium-sized	< 250	≤ € 50 m	≤ € 43 m
Small	< 50	≤ € 10 m	≤ € 10 m
Micro	< 10	≤ € 2 m	≤ € 2 m

2.4.2 Industry organisations / associations

PNEUROP

Pneurop is the European committee of manufacturers of compressors, vacuum pumps, pneumatic tools and allied equipment, represented by their national associations. Its members are national associations representing more than 200 manufacturers in 8 EU Member States, in Switzerland and in Turkey.

Pneurop Members are [75]:

- Association of the Austrian Machinery and Metalware Industries (FMMI)
- Belgium AGORIA
- The Federation of Finnish Technology Industries
- Profluid
- VDMA
- Italy ANIMA
- Sweden TLG
- Switzerland SWISSMEM
- Association of Machine Manufacturers
- UK British Compressed Air Society Limited

These national associations represent more than 200 manufacturers in 8 EU Member States, in Switzerland and Turkey. The European combined market turnover for the businesses represented exceeds 20 billion euro.

The Pneurop association knows several working groups, these being:

- Compressors
- Tools
- Vacuum technology
- Pressure equipment
- Air treatment
- Process compressors

[75] http://www.pneurop.eu/index.php?pagename=Pneurop_Member_Associations_and_Contacts

CAGI

CAGI is the 'Compressed Air & Gas Institute, located in the USA. Many of the Compressed Air and Gas Institute's activities are carried out in its separate sections, which are categorized by product scope. Individual member companies may affiliate with one or more of these sections, depending upon their product lines. Current sections are Air Drying and Filtration, Blower, Centrifugal Compressor, Pneumatic Tool, Rotary Positive Compressor and the Reciprocating Compressor Section. In addition, important work of the Institute is carried out by committees including the Educational and Promotional/Marketing Committee, Standards Committee and Energy Efficiency Committee[76].

Companies in the ' Rotary Positive Compressors' section manufacture compressors and vacuum pumps which operate on several different principles, although all employ positive displacement and rotary motion. Included among these products are rotary positive displacement compressors greater than 2 bar discharge pressure and vacuum pumps that develop vacuum over 28" Hg. Such compressors may be oil free, forced-feed lubricated, or liquid injected, including, but not limited to sliding vane, lobe-type, liquid piston and helical screw. These compressors are stationary type or transportable (as distinct from engine driven portable compressors). In single and multistage configurations, these compressors are used in a wide variety of applications[77].

'Rotary Positive' Members:

- ALMiG USA Corporation
- Atlas Copco Compressors LLC
- BOGE America
- Chicago Pneumatic Tool Co.
- Elgi Compressors USA, Inc.
- FS-Curtis
- DV Systems Inc.
- Gardner Denver, Inc.
- Ingersoll Rand
- Kaeser Compressors, Inc.
- Mattei Compressors
- Quincy Compressor
- Sullair
- Sullivan-Palatek, Inc.

The 'Centrifugal' section includes integrally geared, multi-stage centrifugal air compressors. Unlike positive displacement compressors, these compressors develop pressure by dynamic action. Centrifugal compressors are inherently oil-free and used in a wide range of industrial and process applications where large volumes of high quality air are required[78].

The typical horsepower range for these products is 300 to 3000 HP (roughly 225 kW– 2.2MW). While normally driven by an electric motor, these compressors can also be driven by other means such as diesel engines or steam turbines.

---

[76] Source: http://www.cagi.org/about/background.aspx

[77] Source: http://www.cagi.org/about/sections/rotary-positive-compressors.aspx

[78] Source: http://www.cagi.org/about/sections/centrifugal-compressors.aspx

'Centrifugal' Members:

- Atlas Copco Compressors LLC
- FS Elliott Co., LLC
- Ingersoll Rand

The 'Blower' section of CAGI includes rotary positive displacement blowers and centrifugal blowers in air or gas applications developing up to 28” Hg vacuum or up to 30 psig discharge pressure (is 2 bar, presumably gauge pressure, or 3 bar(a))[79].

'Blower' Members:

- Atlas Copco Compressors LLC
- Gardner Denver, Inc.
- Howden Roots
- Ingersoll Rand
- Kaeser Compressors, Inc.
- Sulzer Pump Solutions, Inc.
- Tuthill Vacuum & Blower Systems

Compressor units within the scope of 'Reciprocating Compressors' are most frequently used for general purpose compressed air supply for applications in manufacturing, fabrication, assembly, automotive, construction, petroleum, natural gas, mining, painting, mobile service, shop service, farm service, home hobbyists as well as many others. Compressor units are typically tank or baseplate mounted, and driven by an electric motor or an internal combustion engine. Products of this section also include all single & two stage basic compressor pumps. The pressure range for products in this section are 3.5 – 14 bar(50-200 psig)[80].

'Reciprocating' Members:

- Atlas Copco Compressors LLC
- FS-Curtis
- DV Systems Inc.
- Gardner Denver, Inc.
- Ingersoll Rand
- Quincy Compressor
- Saylor-Beall Manufacturing Co.

2.4.3 Sales structure

Low pressure and/or oil-free compressor packages are placed on the market through various sales channels:

1. Direct sales: This channel covers the direct sales of manufacturer to end-customer. This is a usual form for sales of especially larger equipment (starting from say 150-200 kW input power) up to MW range where guaranteed performance is a common part of the sales agreement. Servicing and maintenance contracts are often included in the sales agreement.
2. Independent distributors: These distributors sell multiple brands. They often combine sales with technical and service support.

[79] Source: http://www.cagi.org/about/sections/blowers.aspx

[80] Source: http://www.cagi.org/about/sections/reciprocating-compressors.aspx

3. Air centres (dealers): These are retail outlets that only sell equipment from a single manufacturer and may be part of the manufacturers sales organisation.
4. Merchandising team: These are manufacturer's representatives, catering to retail chain stores and catalogue houses.

Additionally, there are sales channels through:

5. OEM "packagers": These companies mainly buy air ends (most often they are active in the low pressure market) and produce a package according clients' specifications.
6. Contractors or service providers: These companies do not sell equipment, but 'compressed air' as commodity or specify equipment as part of a larger engineering project. The contractor or service providers are responsible for equipment specification, selection, installation, service and repair and replacement. Examples of service providers are Praxair, Dalkia.

These two parties are thought to purchase compressors directly from manufacturer's sales representatives.

The preferred sales channel is also partly dictated by compressor technology: For example reciprocating compressors are –in general- more service intensive than rotary equipment (require reed valves, etc.) and technical support is usually part of the offer / purchase.

The buying behaviour can be split up into three main types[81]:

1. Buying large compressors requires presenting detailed specification, high technical expertise, and co-ordinated sales effort. As machine failures can be very costly the service requirements are more complex (availability of spare parts or replacement within 'x' hours, etc.).
2. For medium and small compressors the demand for specifications is less and the buying behaviour is also less complex. Off-the shelf availability is more often a priority to meet tight delivery deadlines. Spare parts are preferably locally available and service for customers is performed without maintenance teams.
3. For small compressors (indicatively less than 3.7 kW / 5 hp) the buyer uses the equipment for relatively small jobs and has little technical knowledge of the equipment. Buyers may be reached through retail outlets.

It could be that a single company owns multiple sales channels (e.g. a direct sales team and a dealer network) that are active in overlapping markets requiring alignment and coordination of these sales channels.

The turnover or sales volume per channel is not known (not public information because of confidential nature) but it can be assumed that the largest equipment is usually sold as direct sales, whereas the smallest equipment is more often sold through retailers and dealers. For small equipment it is quite uneconomical to keep a sales force afloat.

Based on a single reference[82] the respective shares of the main sales channels are:

1. Direct sales: 30%;
2. Independent distributors (may also sell other brands): 35%;
3. Air centres (single manufacturer only): 20%;
4. Merchandising team, manufacturer representatives: 15%.

This source thus shows that manufacturer personnel is responsible for some 3/3 of sales. The more recent US DoE study on air compressors shows that the sales handled by manufacturer personnel has increased to over 90% (see table below).

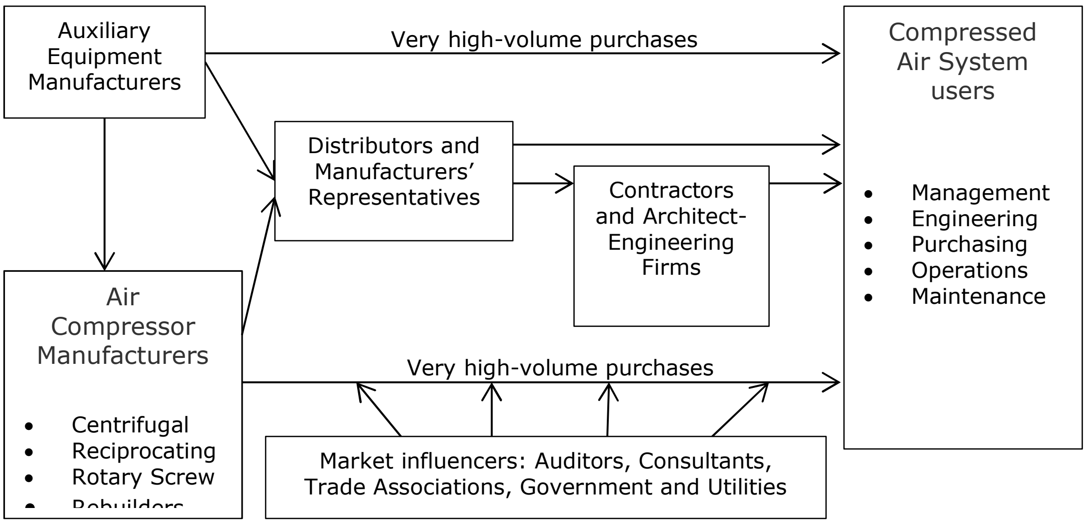
Table 39 Compressor distribution chain[83]

[81] This is based on: http://www.slideshare.net/amoltshirude/ingersoll-rand-25087563. Note: the data in the document is almost 30 years old. We have however not received comments that the text needs changing.

[82] http://www.slideshare.net/AshishMalik6/gp-5-ingersoll-rand. Note: the data in the document is almost 30 years old.

Sales channel				Lubricated rotary PD compressors < 236 l/s	Lubricated rotary PD compressors ≥ 236 l/s
Manufacturer			Customer	7.5	20
Manufacturer	Distributor / manufacturer representative		Customer	85	77.5
Manufacturer	Distributor / manufacturer repr.	Contractor	Customer	5	2.5
Manufacturer	Other/retail		Customer	2.5	0
Total					

Figure 11 Sales structure of compressor market



2.4.4 Trends in low pressure

The low pressure market is characterised by increased competition between centrifugal compressors (specifically the high speed single stage type) and lobe compressors, which both serve the market for very low pressure (between 300 – 800 mbar(g)) and high volume flow rates. A typical application is air for aeration basins of waste water treatment facilities.

When comparing for the same working condition, a properly selected centrifugal type compressors may run more efficient, but centrifugal compressors have (in general) a smaller flow control range[84] and are more susceptible to changing environmental conditions (inlet air temperature, humidity, etc.). Furthermore prices are much higher than for lobe compressors.

In the low pressure market, but in particular for pressures above 800 mbar(g) the lobe compressor is also seeing increased competition from low-pressure screw compressors.

[83] [6450-01-P] DEPARTMENT OF ENERGY 10 CFR Parts 429 and 431 [Docket Number EERE-2013-BT-STD-0040] RIN 1904-AC83 Energy Conservation Program: Energy Conservation Standards for Air Compressors AGENCY: Office of Energy Efficiency and Renewable Energy, Department of Energy. ACTION: Final rule.

[84] See also Task 4, section 4.3 for a discussion of flow control of centrifugal compressors.

2.4.5 Trends in oil-free

According 'Editor Helsinki' the size of the market for oil-free air is currently 30% and is expected to grow to 50% by 2050 [85]

Markets requiring oil-free air (at standard air pressure levels) see a trend towards using intrinsically oil-free packages instead of lubricated equipment (combined with adequate filtration). Drivers for the demand for "oil-free" are client perceptions of risks of possible oil contamination (and subsequent legal and economic consequences). Key-words are risk-free, worry-free, trouble-free.

This doesn't mean that oil-flooded packages, combined with appropriate air treatment, are not capable of also achieving acceptable low oil contamination levels. The difference is in the perception of the risk of contaminated end-products, production stoppages and avoiding reputation damage (contaminated products, recalls) in the event of failure of air treatment equipment, creating worries and troubles.

According *Frost and Sullivan*[86] the reasons for customers preferring 'oil-free' equipment is that they:

- have growing anxiety against law-suits relating to sub-standard products caused by air containing oil particles, as experienced in medical and food industries;
- focus on compliance with environmental regulations (e.g. related to treatment of compressed air condensate of oil-flooded equipment);
- see potential for energy saving and efficiency[87].

Purchase costs of oil-free compressors are generally significantly higher. Maintenance costs for oil-free may be lower as no regular oil filter replacement and oil change is required, but refurbishment may be more frequent.

Lubricated air compressors introduce three forms of oil contaminant into the compressed air stream: aerosol droplets, vapour and liquid (wall flow). By contrast, oil-free compressors introduce no (extra) oil contaminants whatsoever.

2.5 Consumer expenditure base data

This section presents data to be used for the economic analysis in Task 5 life cycle costs and Task 6 Design options.

2.5.1 Acquisition costs

Purchase prices

Compressor manufacturers in Europe were asked to provide purchase prices (street prices) and other costs related to purchasing, operating and discarding relevant equipment. In the same survey VHK also asked for information on performance parameters to derive price elasticity factors for energy efficiency.

VHK identified the following purchase prices (excl. VAT), in relation to average package power input (kW) and isentropic efficiency (%) of the equipment (based on weighted average for power and efficiency in various operating points – see Task 3).

The resulting street prices are expressed as surfaces using a production function expression as follows.

Equation 7 Purchase price of packages per flow control category

[85] https://issuu.com/editorhelsinki/docs/professionals_q1_2016 (p.15)

[86] http://www.reliableplant.com/Read/22951/Report-oil-free-compressors-clear, based on study by Frost and Sullivan http://www.frost.com/sublib/display-report.do? search=oil+free+compressor

[87] The publicly available information does not state the reason for this statement. In the present report the statement is given 'as is'.

Purchase price (EUR, excl. VAT) = EXP(A + (b1*(LN(eff*100)^ b2)) + (c1*(LN(power*100)^ c2)))

Where:

eff =Isentropic efficiency (%), over stated operating range, weighted as in Task 3

power = Input power to package (kW), over stated operating range, weighted as in Task 3

A, b1, b2, c1 and c2 = parameters

Table 40 Parameters for calculating purchase prices, by power (kW) and efficiency (%)

	LP_ZFCR	LP_ZFCRP	LP_LFCR	LP_WFCR	OF_ZFCR|A	OF_ZFCR|W	OF_LFCR	OF_WFCR|A	OF_WFCR|W
A	0.04	0.08	0.00	0.00	0.01	0.02	0.00	0.00	0.00
b1	1.80	2.00	2.00	1.75	0.50	0.49	0.23	0.10	0.10
b2	0.70	0.60	0.60	0.70	1.30	1.30	1.70	1.25	1.10
c1	0.95	0.74	0.54	0.50	2.45	2.20	2.50	4.00	2.89
c2	0.80	0.94	1.09	1.11	0.51	0.56	0.55	0.43	0.58

This results in the following purchase prices for 'average' products per flow control range category.

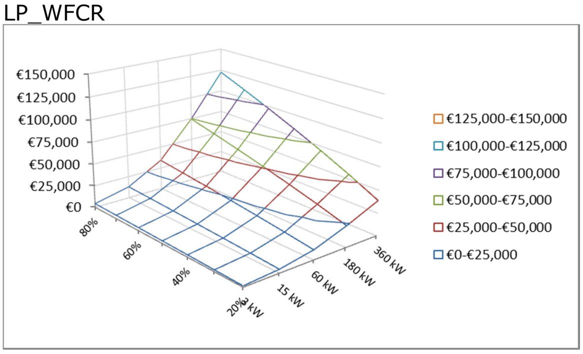
Table 41 Purchase prices (street price, EUR/piece)

	LP_ZFCR	LP_ZFCRP	LP_LFCR	LP_WFCR	OF_ZFCR|A	OF_ZFCR|W	OF_LFCR	OF_WFCR|A	OF_WFCR|W
Avg. power input	8.9	23.5	58.4	29.4	13.5	50	132	51	55
Avg. efficiency	38.2%	51.9%	68.6%	56.7%	44.1%	67.4%	61.2%	56.0%	62.2%
Avg. Street price	€7,219	€16,599	€34,150	€15,791	€13,927	€35,860	€72,336	€37,430	€38,239

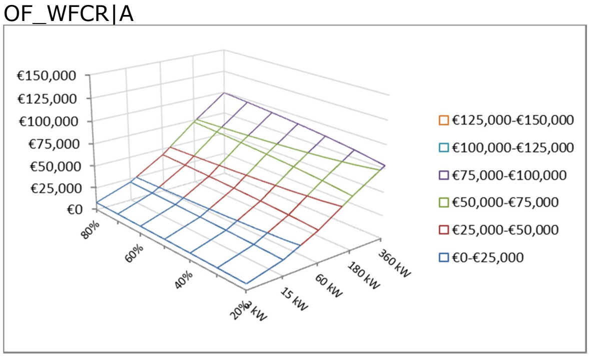
And this allows drawing the following surfaces.

Figure 12 Cost surfaces

LP_WFCR

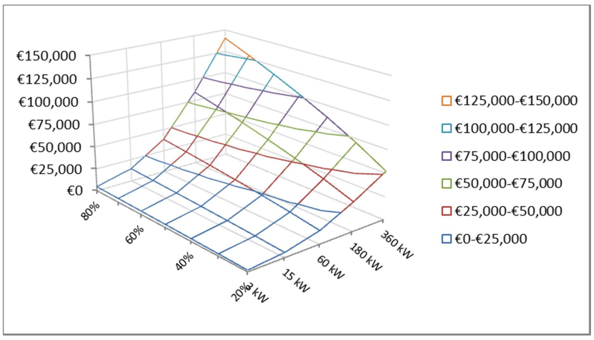


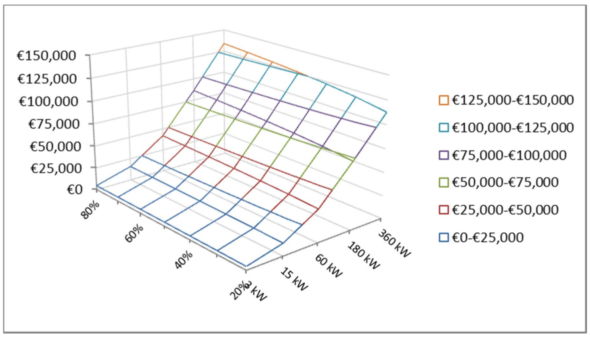
OF_WFCR|A



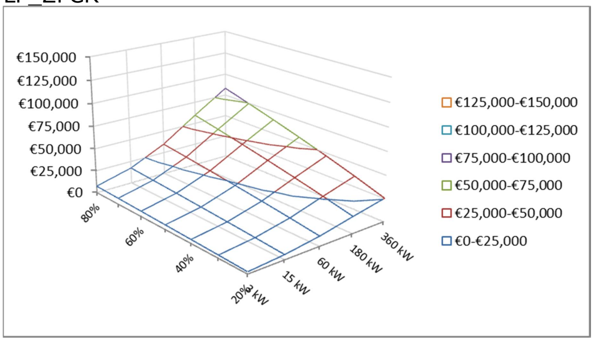
LP_LFCR

OF_WFCR|W

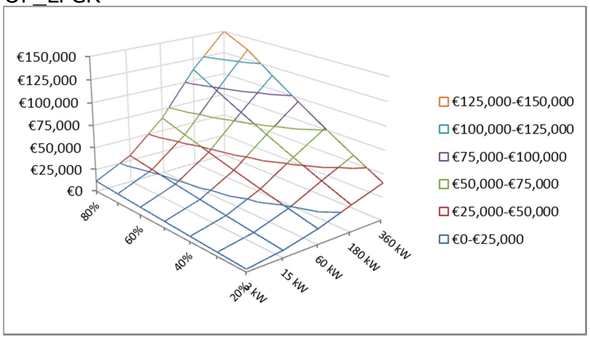




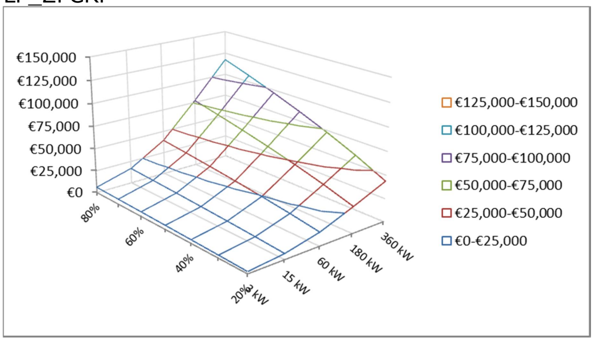
LP_ZFCR



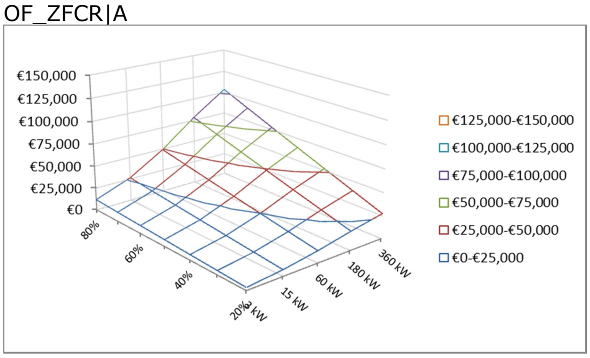
OF_LFCR



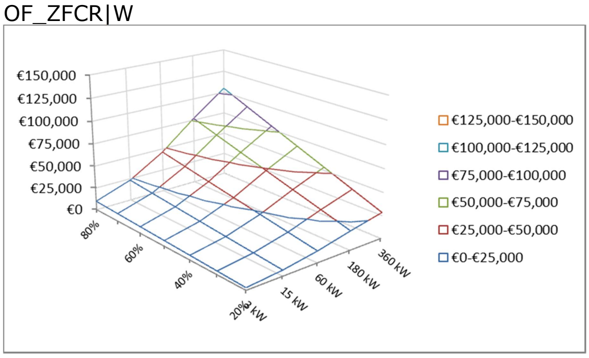
LP_ZFCRP



OF_ZFCR|A



OF_ZFCR|W



Note: The above equations and calculation factors are an approximation and ignore significant differences between compressor technologies as the approach is in principle technology neutral. It does not show the significant spread in compressor prices at similar performance points, as certain technology and package aspects and product characteristics that determine real life costs to a large degree are not represented.

A sensitivity analysis (performed under Task 6) analyses effects of lower and higher purchase prices on overall life cycle costs.

Installation costs

Installation costs are mainly linked to equipment size. The below equation is used to estimate installation costs for both low pressure and oil-free compressor packages.

Equation 8 Installation costs

Installation costs [EUR] = 10*Input power [kW] + 800

2.5.2 Operating costs

Electricity prices for commercial/industrial users

The energy rates are sourced from the MEErP 2013 study. From 2014 and onwards an overall escalation rate of 4% per year is used (energy price growth rate corrected for inflation) based on price trends before 2014. The rates are based on tariffs 'excluding VAT and other recoverable taxes and levies'.

Table 42 Electricity prices for industry[88]

Rate	1990	2000	2010	2020	2030	2040	2050
Non-residential	0.12	0.08	0.10	0.15	0.22	0.33	0.48

The above values relate to:
Annual consumption: 500 MWh < Consumption < 2 000 MWh
EA11-2000, EA12-2006, EA13-2007, EA15-2008, EA16-2010, EA17

Rates for water and fossil fuels are not relevant.

Maintenance & repair costs

Many industry sources state the annual maintenance & repair costs are between 5-10% of the investment costs. Assuming the lower value applies to dynamic compressors, the higher value to reciprocating compressors and a middle value for rotary compressors, the maintenance and repair costs per flow control category are (assuming sales as identified per technology and flow control category):

Table 43 Maintenance & repair costs (annual costs, as % of purchase costs)

Category	LP_all	LP_ZFCR	LP_ZFCRp	LP_LFCR	LP_WFCR
Annual costs (as % of purchase costs)	6%	6%	8%	5%	7%
Category	**OF_all**		**OF _ZFCR**	**OF _LFCR**	**OF_WFCR**
Annual costs (as % of purchase costs)	9%		9%	5%	9%

Inlet filter cost

Inlet filter costs for both low pressure and oil-free compressors were based on the assessment of the previous Lot 31 study[89] and are estimated to be:

Equation 9 Filter costs

[88] Source Eurostat (nrg_pc_205, nrg_pc_203) (MEErP report part 1 page 46)

[89] Ecodesign Preparatory Study on Electric motor systems / Compressors DG ENER Lot 31, FINAL Report of Task 6, 7 & 8, Task 7, page 52, section 2.6.3, 3 June 2014.

Inlet filter costs [EUR] = 1.5*Input power [kW] + 30

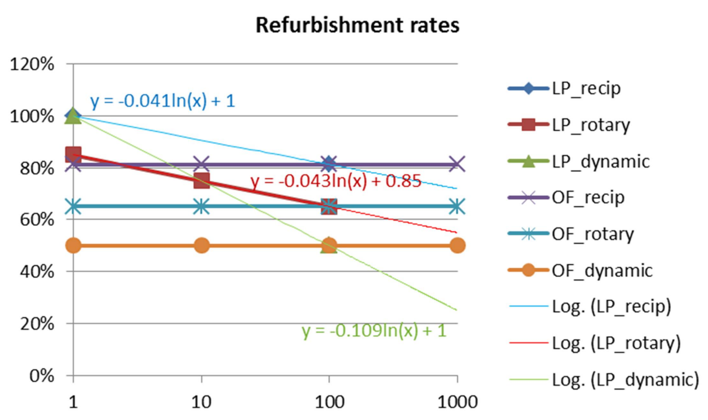
Refurbishment costs

Refurbishment and/or remanufacturing means a combination of cleaning, extensive maintenance and/or repair for the purpose of restoring the performance of product to 'as new' conditions, often with a guarantee. Refurbishment can apply to essential parts of the package (such as remanufacturing the air-end, no change in ownership) but can also apply at the package as a whole (often for the purpose of reselling).

It is difficult to say when equipment needs to be refurbished and what the costs are as much depends on the actual use of the product (duty cycles, maintenance, operating conditions, etc.). Of course the complexity of the product, together with running hours, poor ambient conditions and poor maintenance reduce the expected life before refurbishment.

For the purpose of the life cycle cost analysis (Task 6, life cycle costs) it is assumed that refurbishment rates (the additional costs for refurbishment over product life, expressed as % of purchase costs) depend on technology and size. The following assumptions have been made on the basis of pricing information collected from manufacturers.

Figure 13 Refurbishment rates in relation to compressor technology and size (kW input power)



When combined with the sales volume per technology (see section 2.3.1) the refurbishment rates per flow category are calculated as follows:

Table 44 refurbishment costs per flow control category

Refurbishment costs (over product life)	as % of purchase price
LP_WFCR	68%
LP_LFCR	56%
LP_ZFCR	76%
LP_ZFCRpeak	71%
OF_WFCR/air	71%
OF_WFCR/water	
OF_LFCR	50%
OF_ZFCR/air	75%
OF_ZFCR/water	

2.5.3 Disposal costs

Disposal costs are assumed to be related to product mass. The average mass is approximated by the following equation representing the relation between input power (kW) and mass (kg):

Equation 10 Mass of product (kg) by power (kW)

Mass [kg] = 30*Input power [kW]^0.9

Costs for disposal are assumed to be zero or net positive, as most equipment has residual scrap value. The scrap value of various metals from two information sources is shown in the table below.

Table 45 Scrap metal prices (EUR/kg)

Metal (#) = MEErP code	Scrapmonster[90]	kh-metals[91]
high alloy steel (26)	0.58	0.11
low alloy steel (23)	0.17	0.11
unalloyed steel (22)	0.13	0.11
cast iron (24)	0.12	0.09
aluminium (27)	0.58	0.6
copper (29)	3.03	3.7
plastics (11)	0.00	0
insulation material (16)	0.00	0
electronics (98)	1.00	1
others	0.00	0
assumed powder coating (40)	0.00	0
assumed rubbers (17)	0.00	0
assumed Cr-plating (41)	0.00	0

Using the first Lot 31 study as indicative material input data for a low pressure type compressor, motor rating 47 kW, product mass 1048 kg (data from first lot 31 study, task 5, page 180), a scrap value of a low pressure compressor of 280 euro was calculated (average 0.27 euro/kg). A typical oil free compressor of 189 kW and mass 3722 kg would result in a scrap value of almost 1000 euro.

Combining the factor 30 with 0.27 euro/kg results in factor 8.1 to be used in a kg to euro calculation.

Equation 11 Disposal costs (revenue)

Material value [EUR] = 8.1*Input power [kW]^0.9

The material value however does not take into account dismantling, transport and waste treatment costs (cleaning, separation, shredding, etc.).

Costs for dismantling have been estimated on the basis of the 2011 US dismantling cost study "Xcel" for generating stations[92]. This study breaks down dismantling costs into labour costs

[90] http://www.scrapmonster.com/european-scrap-prices, accessed 23 March 2016, 1 tonne = 1000 kg, 1 USD = 0.89 EUR.

[91] http://www.kh-metals.com/scrap-metal-prices, accessed 23 March 2016.

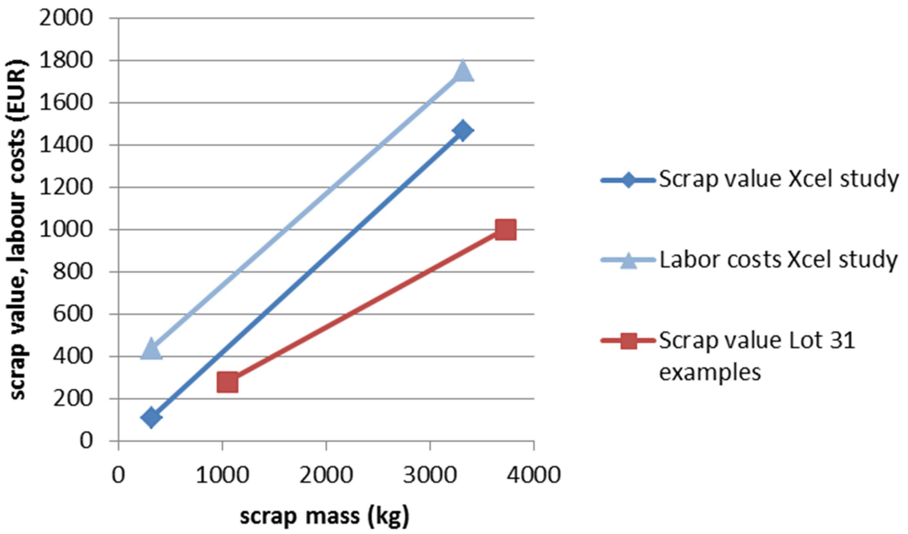
[92] DISMANTLING COST STUDY for (multiple) GENERATING STATIONS, by TLG Services, Inc. for Xcel Energy, September 2011.

(hours and disposables) and scrap value, including transport. Dollars have been converted to euros assuming 1 USD = 0.75 EUR (study values relate to year 2010).

The figure below shows the results (combined with the Lot 31 examples described in the paragraphs above) for dismantling a 300-1000 pound pump (#27 in table D) and a 1000-10.000 pound pump (#28) respectively the lower and higher value. Pumps have been selected as example as no costs for dismantling of compressors were presented. The pumps were deemed the closest match.

The figure shows that labour costs consistently outweigh scrap value. The Xcel study shows that also on a larger scale the decommissioning of plants result in net costs, not benefits.

Figure 14 Scrap value versus disposal costs



Therefore the net cost or benefit of disposal largely depends on factors such as transport and labour costs:

In the Xcel study costs for transport of scrap varied from 30-40% of the total scrap value of carbon steel, to some 1-4% of stainless steel and copper scrap (including copper alloys), to some 13% of the scrap value of electric motors. The less valuable the scrap is, the lower the transport costs need to be to keep the business profitable.

Labour costs vary per region/country. Following this, it can be imagined that dismantling may be profitable in a country with relatively low wages, and less profitable in countries with relatively high wages (assuming the same scrap value applies).

The overall conclusion is that dismantling is likely to result in net costs (based on similar industrial products like pumps) and depends to a high degree on factors that cannot be controlled by the equipment manufacturer (such as transport distances, labour wages and scrap value price).

TASK 3: Users

3 Users

3.1 Introduction

This Task 3 describes aspects that relate to the impacts during the use-phase. The aspects relate to:

1. Strict product/component level;
2. Extended product level;
3. Technical system level.

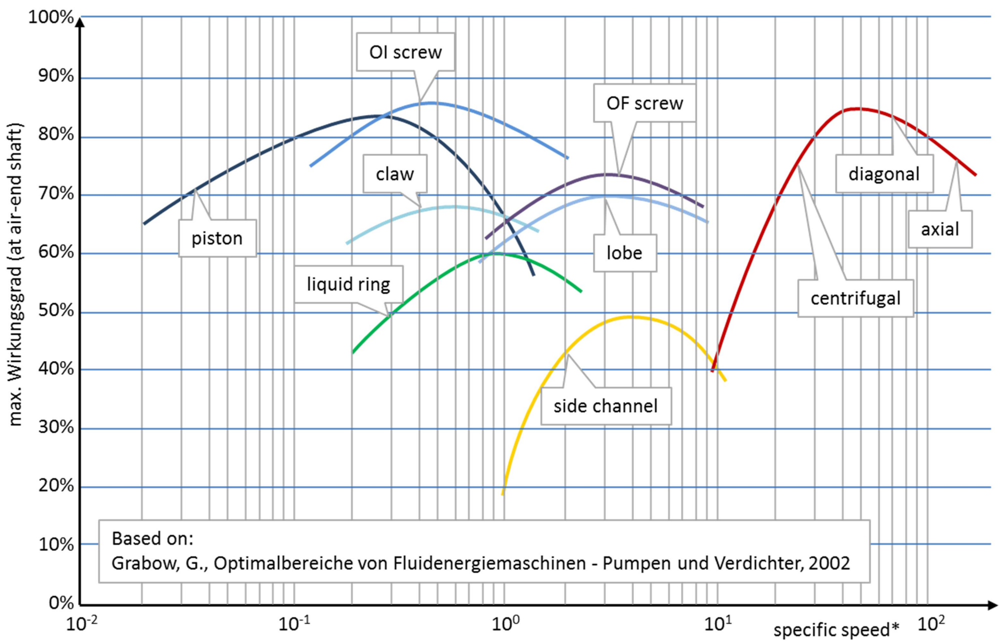
Additionally Task 3 also describes the end-of-life and opportunities or barriers relating to the local infrastructure.

3.2 Strict product/component level

The strictest product/component level is the air-end itself. The electric motor, transmission, motor drive and various package elements (coupling, valves, filters) are not considered at this level.

IMPORTANT: The figure below does not show the relation between the efficiency of a product under similar conditions (flow, pressure). One cannot conclude on the basis of this figure alone that a specific technology is more efficient than another.

Figure 15 Maximum efficiencies of air-end technologies, by specific speed



3.3 Extended product level

The extended product level covers not only the air-end, but also the electric motor, the coupling between air-end and motor (transmission), motor drives and various other items that need to be incorporated for a fully functional package, that can operate safely and reliably within given conditions. The physical boundaries of the extended product are effectively the boundaries of the packaged product.

Apart from including package losses (from the electric motor, coupling, valves, drives, piping, filters) the extended product approach also allows to take into account part load operation as it can include the operating conditions (fixed or variable flow, fixed or variable pressure, effect of changing ambient conditions, frequency of start-stop, etc.). This will be linked to the typical applications as much as possible and forms the main subject of this Task.

It also allows taking into account typical operating characteristics such as annual operating hours and/or load factors that may differ between the various categories of flow/pressure control.

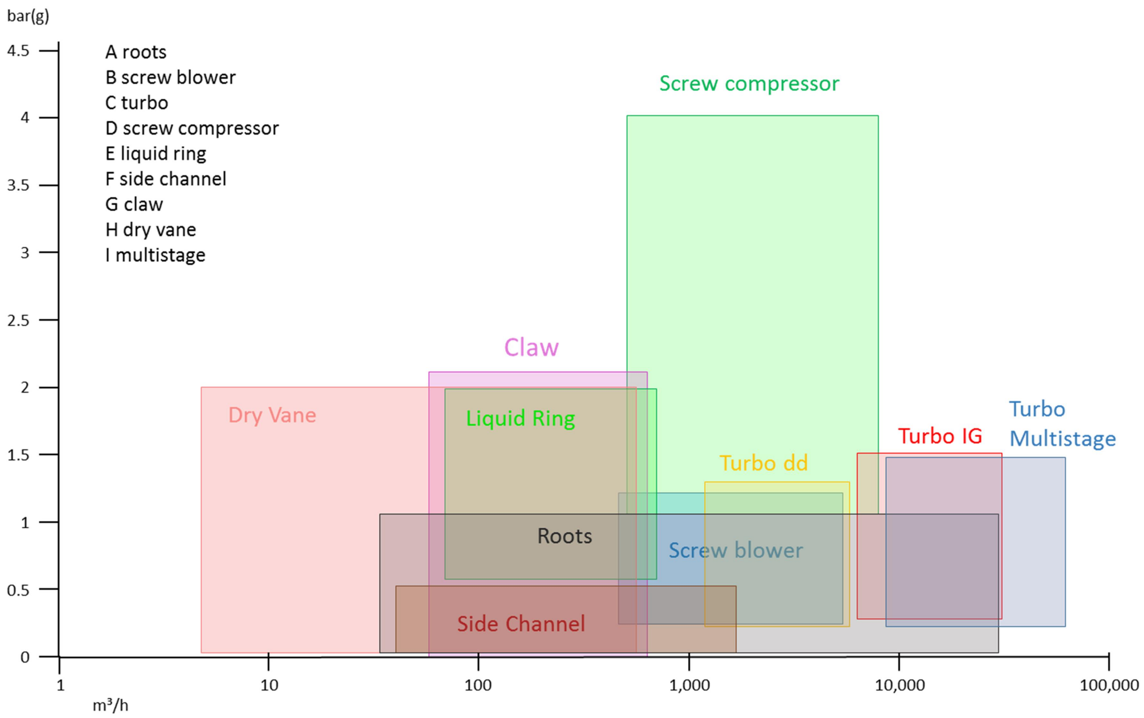
Typical applications of low pressure and oil-free compressed air are described in the following paragraphs.

3.3.1 Low pressure applications

One of the main reasons for the variety in compressor technologies in the application ranges considered is that each technology has its optimal operating envelope and characteristics that make them particularly fit (or unfit) for certain applications.

The figure below shows the range in performances (pressure, volume flow) for the low pressure and oil free application range.

Figure 16 Low pressure technology map (units: bar(g) and m³/h)



The 'low pressure' figure shows that dynamic compressor technologies are more prevalent in the lower pressure ranges, but serve a broad volume flow range. The figure also shows that positive displacement compressors are more prevalent in the lower volume flow rate ranges, and can achieve higher pressures. The highest pressures, still below 5 bar(a) are achieved with screw compressors (not to be confused with screw blowers which are applied up to max. 1.5 bar(a)).

Note that "turbo" technologies includes single stage direct drive (Turbo direct drive) and integrally geared (Turbo IG) and multistage types.

Most prominent low pressure applications, as identified and served by multiple manufacturers, are:

1. Waste water treatment (aeration of basins)[93];
2. Pneumatic conveying ('lean phase' and 'dense phase')[94];
3. Flue gas desulphurization (FGD) oxidation air;
4. Aeration reactors;
5. Filter flushing;
6. Air blast;
7. Jet milling;
8. Air knives;

And then there are low pressure applications that are served by a limited number or only a single manufacturer(s);

9. Texturing (processing of yarn);
10. Lime ovens;
11. Pressure swing adsorption;
12. Pneumatic pressing;
13. Soil aeration;
14. Basin/pond aeration (smaller scale than WWT);
15. Drying (of materials);
16. Toughened glass furnace cooling

Other low pressure applications may be found in areas such as:

- filter cleaning, mining and steel industries;
- fluidization;
- pressurization of ballasts.

Typical technologies applied in the abovementioned application ranges have been identified in the below table, including volume flow and pressure control characteristics, and other operating conditions. The technical description of these technologies is given in Task 4 'Technologies'.

[93] See Annex E for more information.

[94] See Annex E for more information.

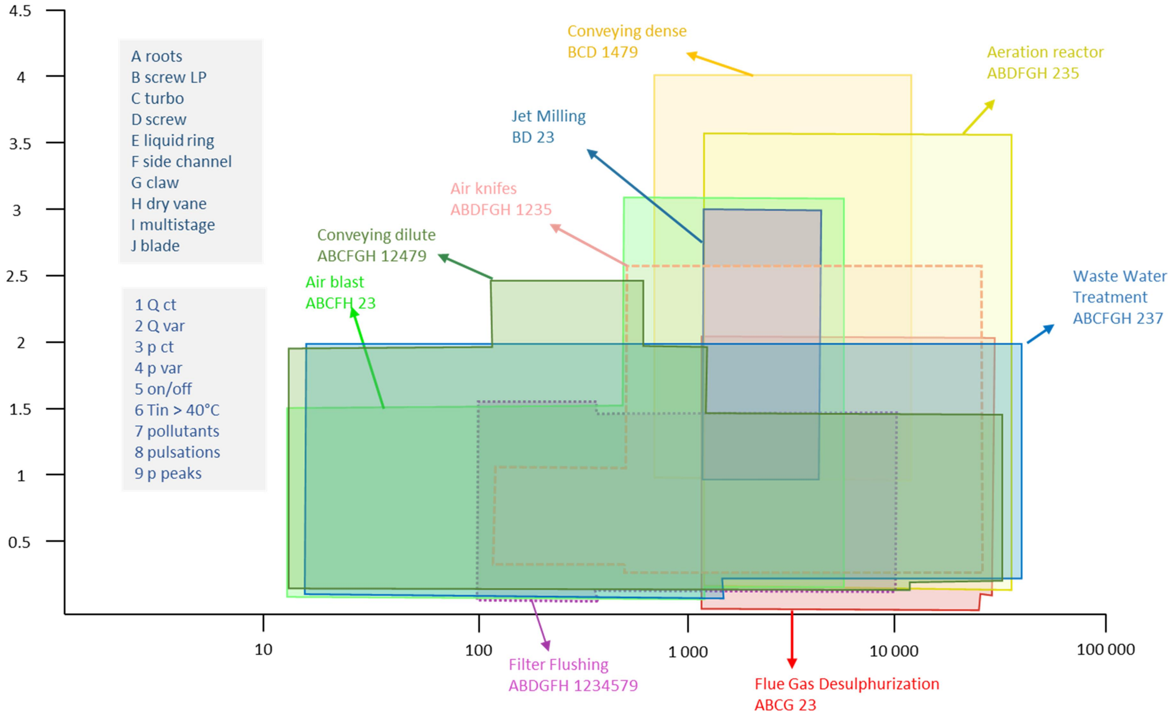
Table 46 Application areas for low pressure air[95]

	Manufacturing industry / Technologies	Waste water treatment	Conveying – lean phase	Conveying – dense phase	Flue gas desulphurization	Aeration reactor	Filter flushing	Air blast	Jet milling	Air knives	Texturing	Lime ovens	Pressure swing adsorption	Pneumatic press	Aeration - soil	Aeration – pond/basin	Drying floor	Furnace cooling
		Multiple manufacturers active									Limited manufacturers active							
--	piston																	
A	lobe (Roots)	x	x		x	x	x	x		x		x	x					
B	screw / low pressure	x	x	x	x	x	x	x	x	x	x	x						
D	screw / dry			x		x	x		x	x	x							
--	screw / water inj.																	
H	vane / dry	x	x			x	x	x		x				x	x	x		
--	scroll																	
G	tooth (also claw)	x	x		x	x	x			x						x		
E	liquid ring															x		
--	axial																	
C	turbo: Single stage	x	x	x	x			x			x	x						
I	turbo: multi-stage /inline																	
--	turbo: MS, multi axis																	
F	turbo: side channel	x	x			x	x	x		x				x		x	x	x
J	'blade compressor'©	x																
Volume flow / pressure control																		
1	volume flow = constant		x	x			x			x		x	x	x	x			
2	volume flow = variable	x	x		x	x	x	x	x	x	x					x	x	x
3	pressure = constant	x			x	x	x	x	x	x	x	x				x	x	x
4	pressure = variable		x	x			x						x	x	x		x	
Other operating characteristics																		
5	on/off					x	x			x								
6	inlet temperature >40ºC																	x
7	pollutants	x	x	x			x											
8	pulsations																	
9	pressure peaks		x	x			x											

In the figure below the typical discharge pressure is plotted versus volume flow range for the different application ranges within the low pressure range.

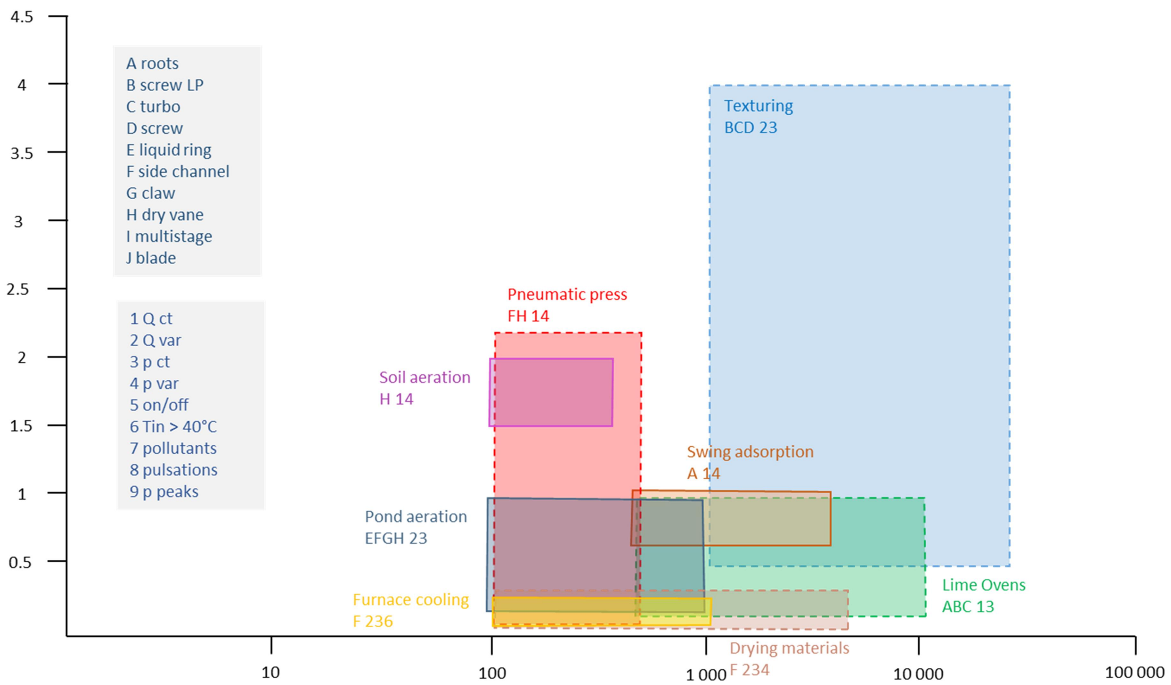
95 Source: PNEUROP JWG, 16 March 2016

Figure 17 Application map low pressure air, multiple manufacturer applications[96]



And for the applications served by a limited number or only a single manufacturer(s):

Figure 18 Application map low pressure air, single manufacturer applications[97]



[96] Source: PNEUROP JWG, 16 March 2016

[97] Source: PNEUROP JWG, 16 March 2016

The following typical usages have been identified in the low pressure application range:

- Variable flow and constant pressure;
- Fixed flow and variable pressure;
- Fixed flow and variable pressure, with pressure peak capability (for pneumatic conveying and filter flushing, see also the Annex on pneumatic conveying).

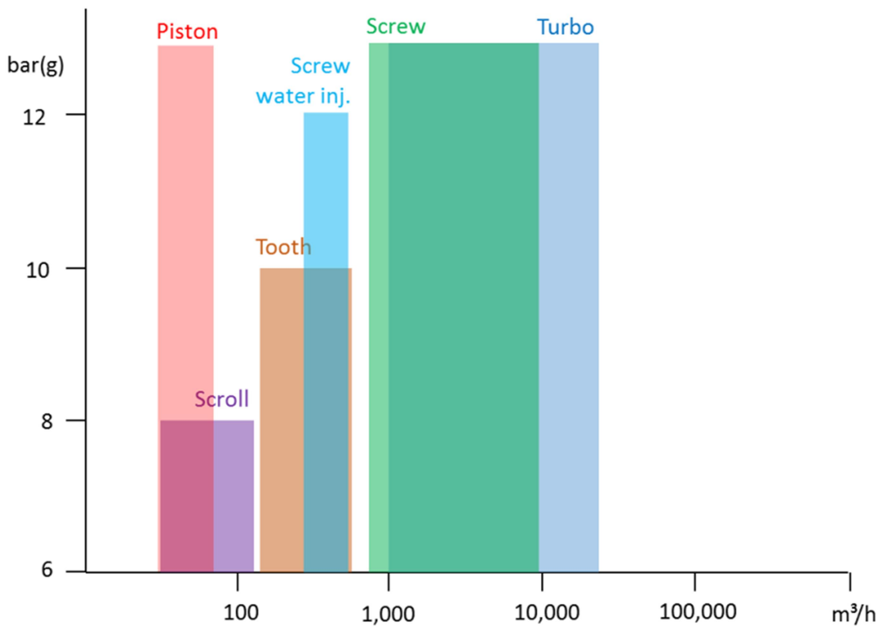
Waste water treatment (aeration) is an example of variable flow and constant pressure. The system curve of a waste water treatment plants is very flat, i.e. requires a nearly constant outlet pressure (which is linked to the column of water in the basins into which the air is pumped, and to a lesser degree, the pipeline losses), but the volume flow may change considerably, depending on the oxygen demand of the water to be treated. As the air inlet temperature and pressure also changes (from day to night, from summer to winter) the system curve is actually not a single line, but an area.

This area can be serviced with rotary positive displacement equipment by using VSD, and by turbo machinery for which there are basically four options: VSD (but in a limited range as with constant pressure the unit must avoid surge conditions), variable inlet guide vanes (mainly to control discharge pressure), variable diffuser guide vanes (mainly to control the volume flow), and the combined use of variable inlet + diffuser vanes.

3.3.2 Oil free applications

In the oil-free application range, pistons stand out as able to achieve very high pressures although at lower volume flow ranges. Going from scroll, tooth to screw shows an increase in both maximum volume flow range as well as maximum pressure attainable. The highest volume flow range at maximum pressure can be achieved by multi-stage turbo compressors (direct drive or geared).

Figure 19 Oil-free technology map



As stated in Task 2, section 2.4.5, the use of intrinsically oil-free compressors is growing. Oil-free air compressors carry a lower risk of oil contamination and are applied in sensitive processes, where the quality of the compressed air is important for the quality of the end-product or the system attached.

This is the case where the compressed air comes in direct contact with the end-product, such as in the handling of foodstuffs, pharmaceuticals, but also packaging of foodstuffs and beverages where risk of contamination is a factor (oil- free 'plant air').

Other application areas for oil-free are processes that require air at the highest cleanliness, such as used for measurement devices and regulated valves ('Instrument air').

If the air itself is part of a process, such as for oxidising or agitation, it needs to be free of contaminants and ('Process air')

The trend is to supply clean (oil, particles, water removed) and dry air for both general 'process' and 'instrument' purposes. This avoids running separate lines for process and instrument air.

The list below gives some application areas for oil-free air.

Automotive

- Surface preparation of objects to be coated, painted
- Spray painting
- Agitation of paint baths
- Assembly robot operation

Chemical

- Fermentation and agitation, as compressed air supplies oxygen to bacteria
- Air separation in PSA (pressure swing adsorption) plants. Oil free avoids oil being deposited in membranes used to separate nitrogen and oxygen and keeps the gases pure.
- PET production - Compressed air is used to produce and transport PET resin beads. Oil contamination in the air will contaminate the resin and affect the composition of the end product when the beads are sintered.
- Pneumatic Transport - Compressed air is used to pneumatically transport materials such as PVC, PTA and DMT chips[98]. Oil-free air reduces clogging, malfunctioning and jamming due to oil contamination.
- Control Systems - Compressed air is used to power control valves and actuators.
- Safety in hazardous processes - In hazardous processes like oxygen generation, compression and use, oil free air helps reduce the risk of explosion. In addition, preventing oil contamination from clogging pneumatic transportation and control systems reduces fire hazards.

Food & beverage

- Product Transportation and Storage - Compressed air pushes foodstuffs, such as powders and cereal, through pipes. Oil-free air ensures higher product purity and eliminates the risk of oil mixing with and contaminating the end product.
- Packaging, Filling and Capping - Compressed air is used for these processes and often has direct contact with the product. Oil-free air prevents oil contamination and is a necessity for aseptic packaging environments.
- Cooling, Spraying and Cleaning - Compressed air is used to cool down baked goods, spray down produce and clean bottles and pipes.
- Fermentation and Aeration - Compressed air supplies oxygen to bacteria for fermentation processes and is pumped into liquids to raise their oxygen content. Oil-free air ensures oil contamination does not kill bacteria and/or fauna living in oxygenated waters.

[98] PTA and DMT are polymers used in PET bottle fabrication.

Pharmaceutical

- Tablet Production and Coating - Compressed air is frequently used to de-dust tablets and spray on tablet coatings.
- Mixing and Holding - Compressed air is used to maintain over-pressurization on mixing and holding tanks to ensure product integrity/sterility.
- Product Filling, Packaging and Bottling - Compressed air often has direct contact with the product and/or package during filling/dosing, blister packaging and bottling.
- Aseptic Applications - Oil contamination can prevent high efficiency particle filters from performing effectively. Oil-free air ensures consistently sterile air.

Oil & gas

- Nitrogen Generation and Buffer Air - Separated with membrane technology, compressed air provides the nitrogen blankets needed in LNG tankers and transfer stations.
- Process Operation - Compressed air is used in gasoline sweetening, sour-water oxidation, catalyst regeneration and sulphur removal. Class 0 100% oil-free air maintains product purity of the end product in such process applications.
- First-Generation Drives and Controls - Compressed air powers first-generation drives and actuates control valves.
- Calibration and Test Equipment - Compressed air is often used to calibrate instrument and safety valve test benches and liquid/gas analysers.
- Safety in hazardous environments - Even a slight trace of oil contamination in the compressed air used to purge EEx control panels can create a flammable situation or lead to a platform shutdown and evacuation

Furthermore, oil-free compressor technologies are also found in applications where there is a large compressed air demand and reduction of energy consumption is important.

Main applications are summarised below[99,100].

Please note that this is NOT an exhaustive overview and more processes in which oil free equipment is used may exist.

[99] Source: http://www.atlascopco.com/

[100] Listlargelybasedon:http://www.ingersollrandproducts.com/am-en/solutions/oil-free/industries-served.LastaccessedDecember2015

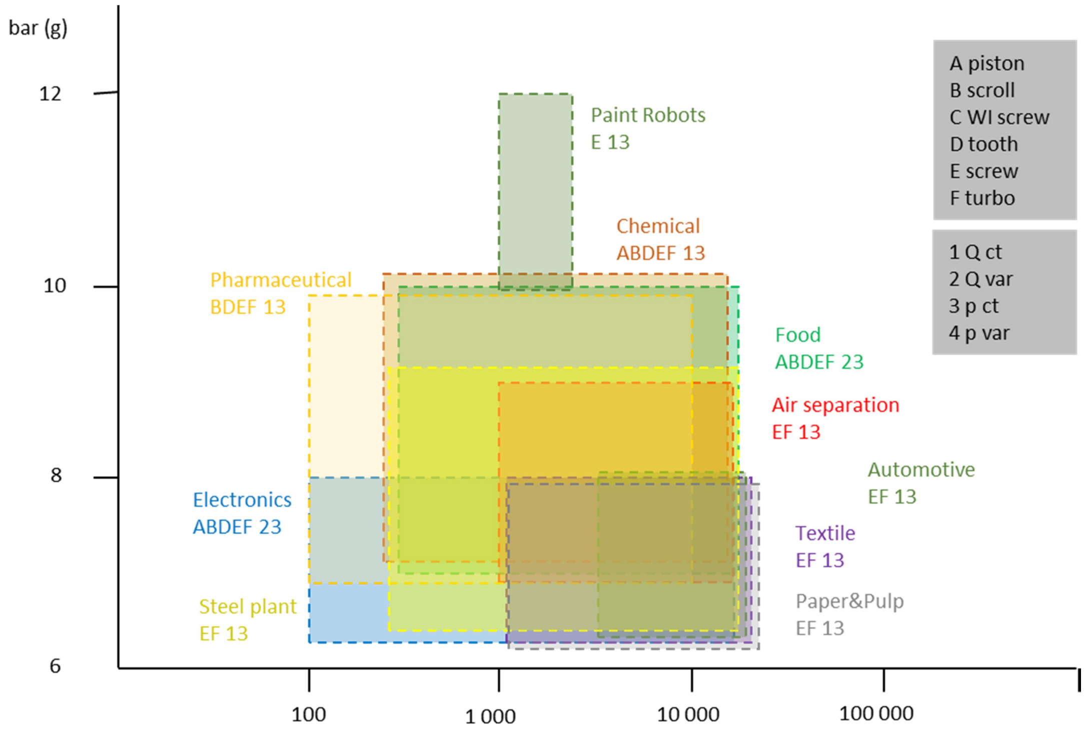
Table 47 Application areas for oil-free air

Manufacturing industry / **Applications**	**a) Air Separation**	**b) Automotive**	**c) Electronics**	**d) Food & Beverage**	**e) Glass**	**f) Metal**	**g) PET Industry**	**h) Pharmaceutical**	**i) Pulp & Paper**	**j) Ski Industry**	**k) Textile**	**l) Waste Water Treatment**
Nitrogen supply	x											
Breathing air	x			x		x						
Instrument air		x	x	x		x	x	x	x			x
Cleaning air		x	x	x			x	x	x			
Cooling air		x			x	x			x			
Process air (tools, robots)		x	x			x			x			
Painting air		x										
Nitrogen soldering			x									
Pneumatic conveying				x			x	x				
Aeration				x				x				x
Fermentation				x				x				
Modified atmosphere packaging				x				x				
Cooling and spraying				x				x				
Packaging equipment				x				x				
Glass blowing					x							
Float glass manufacturing					x							
Combustion air						x						
Sandblasting						x						x
Flue gas desulphurisation						x						
Coating air						x						
PET blowing							x					
Feed air snow guns										x		
Pressure testing										x		
Spinning											x	
Weaving											x	
Dyeing											x	
Texturizing											x	
Winding & coning											x	
Inertisation of sludge digesters												x
Leak testing												x
Cryogenic cleaning												x

The applications most often cited are: Instrument air (8 times), cleaning air (6 times), cooling air and process air (both 4 times), breathing air, pneumatic conveying, aeration (all 3 times) and fermentation, modified atmosphere packaging, cooling and spraying, packaging, sandblasting (all 2 times). Other applications are mentioned once. A larger, more specific, list is presented in Annex E.

Each application area can be characterised by a range in volume flow rate and discharge pressure required. The following figure shows the typical performance ranges for the application areas mentioned above.

Figure 20 Application map oil-free air[101]



Not included in above figure are: glass industry, power plants, sanitary products, metal making, rubber & plastics, ceramics, PET industry, ski industry (making snow).

The table below shows typical application areas and technologies used in such areas.

Table 48 Oil-free application areas and typical technologies

Manufacturing industry / Technologies	Electronics	Food & Beverage	Chemical	Air Separation	Pharmaceutical	Textile	Automotive	Steel production	Pulp & Paper
piston	x	x	x						
lobe									
screw / dry	x	x	x	x	x	x	x	x	x
screw / water inj.	x	x	x						
vane									

[101] Source: PNEUROP JWG, 16 March 2016

Technologies \ Manufacturing industry	Electronics	Food & Beverage	Chemical	Air Separation	Pharmaceutical	Textile	Automotive	Steel production	Pulp & Paper
scroll	x	x	x		x				
tooth	x	x	x		x				
liquid ring									
axial									
turbo	x	x	x	x	x	x	x [a]	x	x
Volume flow / pressure control									
volume flow = constant			x	x	x	x	x	x	x
volume flow = variable	x	x							
pressure = constant	x	x	x	x	x	x	x	x	x
pressure = variable									

[a]: general plant air

Most oil-free applications require constant volume flow, although the areas 'Electronic' and 'Food and beverage' may also require variable volume flow.

Technologies found as typical 'oil-free' compressor are: piston, screw (dry and water injected), scroll, tooth, and turbo compressors.

For oil-free the following typical usages have been identified:

- Fixed flow and constant pressure:
- Variable flow and constant pressure.

3.3.3 Flow control range categories

In both low pressure and oil-free there are applications that require variable flow at constant pressure, and applications that require a fixed flow, possibly under varying pressure conditions. Surveys show[102] that typically compressors in the 50 kW to 150 kW range operate at an average of 50% to 80% of full capacity load for 4,000 hours a year.

This section categorises equipment according these costumer defined conditions, resulting in four categories for low pressure applications and three categories for oil-free applications (later on, the categories for OF_WFCR and OF_ZFCR will be further subdivided into air- and water-cooled).

[102] http://www.plantservices.com/articles/2003/415/

Table 49 Flow control range categories

Low pressure	Oil-free
▪ **Wide Flow Control Range**	▪ Wide Flow Control Range
▪ **Limited Flow Control Range**	▪ Limited Flow Control Range.
▪ **Zero Flow Control Range**	▪ Zero Flow Control Range (including intermittent);
▪ **Zero Flow Control Range with pressure peak capability**	

These categories have been defined as follows:

'Fixed flow' means the product offers no control for changing the volume flow independent of pressure.

These are mainly single speed compressors. Most equipment will probably run in an environment at a fixed pressure. However, it could be that the compressor application requires a capability to handle short-lived pressure peaks (such as may occur in pneumatic conveying). This forms a second group in the fixed flow category.

Whether a compressor has peak pressure capability (only for low pressure / zero flow control applications) depends on its performance under a certain duty cycle. 'Pressure peak capability' is defined as:

- A peak pressure of 200mbar above the maximum pressure;
- The maximum allowable intake volume flow decrease during pressure fluctuations and peaks is 2% per 100mbar pressure increase;
- The maximum allowable reaction time is 1s;
- The minimum allowable peak frequency is 8 times per hour, minimum duration 15s.

'Variable flow' means the compressor package allows an intentional change in volume flow rate, most obviously by VSD but also by adjustable guide vanes in turbo compressors or by valve controls in piston compressors or other means.

The flow control range (expressed as percentage of full load flow) can differ considerably between applications, and hence the technologies applied can differ.

The assessment of flow control ranges resulted in a differentiation between low pressure and oil-free categories as to how wide the volume flow control range is. The reason is that in low pressure applications the technologies may have a wider volume control range than in oil-free applications (higher discharge pressure).

For this study the following forms of intentional volume flow control are defined [103]:

- Limited volume flow control range (LFCR);
- Wide volume flow control range (WFCR).

The difference between 'limited' (LFCR) and 'wide' (WFCR) is defined as a threshold value of the minimum volume flow rate (V_{min} expressed as a % of the maximum volume flow rate, at the same discharge pressure) that can be achieved:

- for low pressure: if $V_{min} \leq 50\%$, "WFCR", else "LFCR";
- for oil-free: if $V_{min} \leq 60\%$, "WFCR", else "LFCR".

[103] The concepts are not described in standards or handbooks. They have been identified by the technical experts that contributed to this study, on basis of consensus.

Table 50 Flow control range categories

	Fixed flow	Fixed flow, with pressure peaks	Minimum flow threshold (as % of maximum flow)	
Low pressure	LP_ZFCR	LP_ZFCRp	LP_LFCR larger than 50% of maximum flow	LP_WFCR smaller/equal to 50% of maximum flow
Oil-free	OF_ZFCR	(not applicable)	OF_LFCR larger than 60% of maximum flow	OF_WFCR smaller/equal to 60% of maximum flow

These categories were also the basis for the data collection by the relevant industries.

3.3.4 Use of compressor packages

This section describes typical use aspects such as operating hours and load factors of the complete and functional compressor package, without auxiliary features such as dryers.

Together with Task 4, which focuses on efficiency, and Task 2, dealing with sales volumes, the data allows assessment of overall energy consumption, as presented in Task 5.

As stated in the introductory remarks, a data collection effort by the industries involved resulted in information describing the product performance.

For oil-free the data collection could only provide results at highest aggregation level, as further subdividing could allow sensitive commercial information to become available in the public domain.

Operating hours

The operating hours are the hours per annum the unit is operational (in 'active mode') and responding to signals that aim to regulate the volume flow and pressure supplied by the package. This mode includes idle- / unload- / offline-modes during which the compressor is not supplying pressurized air into the system, but is still 'active'.

The hours the unit is not operational (or 'active') are the 'off-mode' hours, calculated as (365 days*24 hrs) – operating hours (h/a). Depending on how the compressor is controlled, this means that the compressor during these hours is completely de-energised or that certain parts of the compressed air system remain energised in order to restart the unit effortlessly (begin of operational hours). The energised parts may be present in the compressor package hardware or in an external piece of controller hardware, in the form of relay switches or similar.

The actual power consumption in off-mode is not known (not reported by manufacturers) but experts believe it is likely to be insignificant when compared to full load power (for example, tens of Watts compared to several tens or hundreds of kilowatts). It's relevance for the overall energy consumption is expected to be minimal and means to minimise this consumption are not described in this report.

The operating hours identified by compressor experts are shown in the table in the next section.

Load factor

The load factor is a factor that corrects the 'average loaded power' to a (more representative) actual power consumption during operating hours.

The 'average loaded power' is, for zero flow control, the power at full flow, weighted over the min/avg./max pressure range (see Task 4, section 4.5 for weighing method). For equipment with volume flow control, it is the power weighted over the min/avg./max volume flow range and pressure range). Each operating points has its own weight assigned to it.[104]

The load factor or power correction is required as during the operating hours, the equipment may be in loaded or unloaded condition (see Task 4, section 4.5 for methods of flow control). The unload condition occurs if the required flow is less than the minimum that can be supplied continuously (for example: when a centrifugal compressor reaches its surge limit). As the power consumption in unloaded state is significantly less than during loaded state (how much depends on the control method applied) the load factor is representative of how much the manufacturer expects the unit to be in load/unload conditions.

Industry experts provided estimates for load factors of low pressure equipment by flow categories. For oil-free, only one general load factor was provided, as data at flow category level was considered too sensitive to be put in the public domain.

The operating hours and load factor for oil-free flow categories have therefore been estimated, but in a way that the product of sales*power*load factor * operating hours, still results in the same values as presented by the industry experts for the complete OF group.

Table 51 Operating hours and load factor for base cases

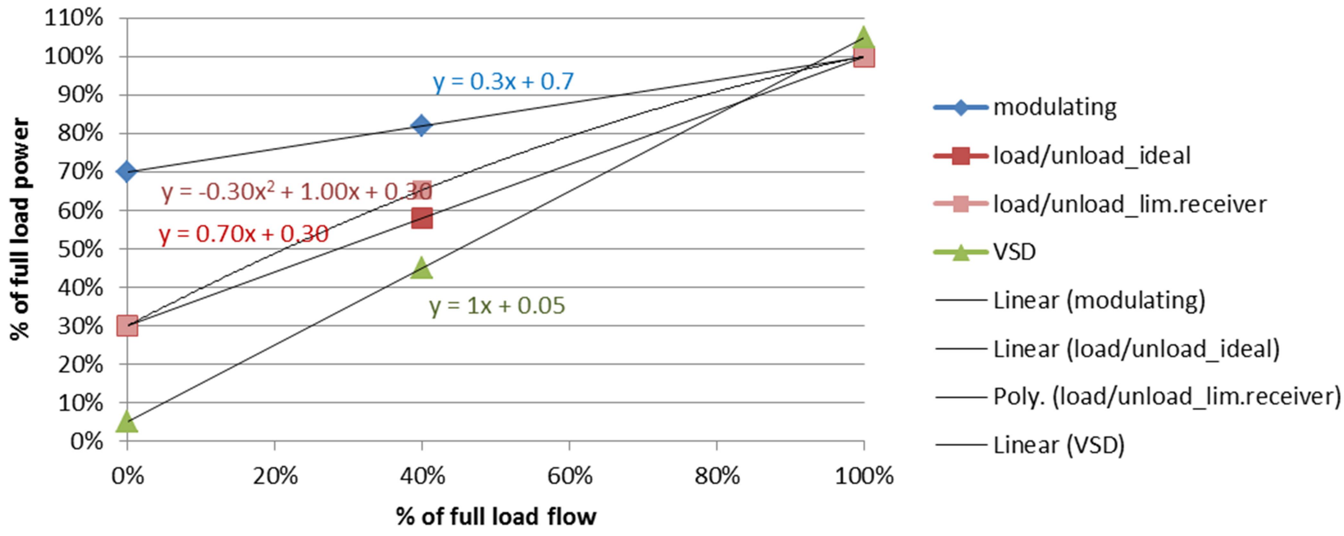
Category	operating hours (h/a)	load factor (-)
LP_ZFCR	3644	0.78
LP_ZFCRp	2688	0.62
LP_LFCR	3902	0.90
LP_WFCR	3943	0.89
OF_ZFCR	3595	0.83
OF_LFCR	3900	0.99
OF_WFCR	3900	0.89

For compressors with a variable speed drive, the number of unload hours will be relatively smaller, hence the load factor is relatively high for the LFCR and WFCR categories.

As an example: A load factor (correction to power input) of 0.78 corresponds with a volume flow of 58% of the maximum flow at 100% of time, for a load/unload control assuming non-ideal receiver capacity. This is explained in the figure below.

[104] In the former Lot 31 study the load factor also corrected for the conversion of motor nominal power (which is shaft power, or output power) to electric input power. This is not required in this present Lot 31 study for low pressure and oil-free as the 'average power' is already an electric input power, not a motor nominal power.

Figure 21 Average power input per average flow, for several types of flow control[105]



The values above are the result of an assessment by experts. There may be differences to operating hours and load factors found in actual systems, as each application is essentially unique.

3.4 Technical system level

This section describes aspects that influence the environmental impacts of the larger system in which a compressor package operates. Through certain features of the compressor the functional performance and/or the resources use and emissions of that larger product system can be affected.

This section discusses aspects related to:

- Energy saving at system level;
- Heat recovery (beyond the compressor package);
- Oil-free compressors versus oil-injected;
- Alternatives to compressed air.

3.4.1 Energy saving at system level

Although the focus of this study is on the packaged product and the (environmental) savings that can be achieved at (extended) product level, one must realise that a much larger energy saving potential can be unlocked by improving the compressed air system itself.

Compressed air is often designated as the fourth utility (next to electricity, gas and water) as it's use is so widely spread. But consumers of compressed air sometimes get the impression that it is 'for free'. Possibly as a result of that notion, it is often wasted despite compressed air being actually a relatively expensive form of utility.

A study from 2001 quantified the savings at package level versus system level. Although the study is over 15 years old, the general conclusions are still considered to be valid.

[105] This graph is created by VHK on the basis of several sources, for example: http://www.nrcan.gc.ca/energy/products/reference/14970 and http://www.airbestpractices.com/system-assessments/end-uses/optimize-compressed-air-system-highly-fluctuating-air-demand

Table 52 Energy savings potential compressed air systems [106]

Energy savings measure	Applicability (1)	Gains (2)	Contribution (3)		Comments
	%	%	TWh/a	%	
System installation or renewal					
Improvement of drives (high efficiency motors)	25%	2%	0,40	0,50	Most cost effective in small (<10 kW) systems
Improvement of drives (speed control)	25%	15%	3,00	3,80	Applicable to variable load systems. In multi-machine installations, only one machine should be fitted with a variable speed drive. The estimated gain is for overall improvement of systems, be they mono or multi-machine
Upgrading of compressor (for instance, to 2 stage compressor)	30%	7%	1,68	2,10	
Use of sophisticated control systems	20%	12%	1,92	2,40	
Recovering waste heat or use in other functions	20%	20%	3,20	4,00	Note that the gain is in terms of energy, not of electricity consumption, since electricity is converted to useful heat
Improved cooling, drying and filtering	10%	5%	0,40	0,50	This does not include more frequent filter replacement (see below)
Overall system design including multi-pressure systems	50%	9%	3,60	4,50	
Reducing frictional losses (for example by increasing pipe diameter)	50%	3%	1,20	1,50	
Optimising certain end use devices	5%	40%	1,60	2,00	
System operation and maintenance					
Reducing air leaks	80%	20%	12,80	16,00	Largest potential gain
More frequent filter replacement	40%	2%	0,64	0,80	
Total[107]				**32,90**	

(1) % of compressed air systems where this measure is applicable and cost effective

(2) % reduction in annual energy consumption

(3) Potential contribution = applicability * reduction, for a total of 80 TWh (calculated as max energy for EU systems)

[106] Compressed air systems in the European Union, Fraunhofer 2009, based on data by Radgen et al, 2001. Note: this study covers standard air packages as well.

[107] Note the potential for savings, 32,9%, is less than the sum of the savings for individual measures. The total possible savings must be calculated as a product of efficiency gains. ES = GEC*IEF*CasF*(1-Πi(1-EGFi*MPFi))

It is not hard to find comments of industry experts about the basic level of knowledge of clients regarding specifying compressors, compressed air systems and servicing/maintenance. Some industry experts have described sobering examples of customer perceptions regarding compressed air [108] [109] even if the savings that can be realised by properly specifying and servicing compressed air systems can be staggering. Sources state it is probably not difficult to find systems in which 20-30% of the compressed air generated is to compensate for leakages.

Experiences with energy audits

In the study "Assessment of the market for Compressed Air Efficiency Services"[110] is stated that:

"Recent experience in a variety of "system optimization programs," as well as the experience of consultants in the field, suggests that over 50% of industrial plant air systems harbour opportunities for large energy savings with relatively low project costs. Compressed air system measures identified in energy audits of small- to medium-sized industrial facilities by the Industrial Assessment Centres had average projected savings of 15% of compressed air system usage with simple paybacks in less than 2 years. Many case studies conducted for system optimization programs have identified savings in the range of 30 to 60% of initial system usage. The United States Industrial Electric Motor Systems Market Opportunities Assessment (Motor Market Assessment) estimated that compressed air system energy use in the typical manufacturing facility could be reduced by 17% through measures with simple paybacks of 3 years or less. In addition to energy benefits, optimization of compressed air systems frequently results in corresponding improvements in system reliability, product quality, and overall productivity."

The DOE website presents various case-studies of more recent years that show that attention to the compressed air system (from compressor inlet to point-of-use) often results in savings with a payback period of several months for several large customers (attention to leakage may be recuperated within 3 months as the Fujifilm example shows).

It is true that customers of compressed air are often (or always) more worried about downtime than ending wasteful practices: In most cases the costs of energy lost do not outweigh the costs of production lost, and energy wastage is accepted.

But sometimes, negligence of proper servicing and maintenance leads to frequent failures and/or more than average servicing / repair and result in disruptions of the primary process. These disruptions may be a more powerful incentive for a client to perform an energy audit of the site, rather than the loss of energy itself. Still, as the studies by DOE shows, in most cases payback rates of less than 2 years are common.

Therefore, regardless whether measures at product level are feasible or not, increased attention to system level savings should be paramount and placed high on the political agendas of all stakeholders.

Text books and studies on saving energy in compressed air systems often quote a savings potential in the range of 20-30% of the total compressed air system energy consumption, which may be realised by:

- Fixing leaks;
- Reducing pressure losses;
- Reducing compressor pressure;
- Other:

[108] http://hydraulicspneumatics.com/200/FPE/SystemDesign/Article/False/6462/FPE-SystemDesign

[109] http://hydraulicspneumatics.com/other-technologies/improving-compressed-air-system-efficiency-part-1?page=2

[110] Prepared for Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory by XENERGY Inc.

Burlington, Massachusetts DOE/GO-102001-1197, June 2001

  - Optimizing running times in multi-compressor setup;
  - Check condensate drains;
  - Review piping system;
  - Replace filters;
- Applying compressed air master controllers;
- Heat recovery.

Fixing leaks

Each mm^2 of air leak results in approximately 0.137 kW extra power requirement at 7 bar working pressure. Only one hundred leaks of just 1 mm diameter (or eleven leaks of 3 mm diameter) in a system already result in some 43 kW extra power. If operated 24/7 at 365 days/year this results in 376 680 kWh energy wasted. At some 0.105 Euro/kWh this is almost 40 thousand euro annually.

Table 53 Extra power requirement by air leak size[111]

Hole diameter		Hole area	Output flow at 7 bar working pressure	Power requirement for the compressor
Size	mm	mm^2	l/s	kW
	1	3.14	1.2	0.4
	3	28.3	11.1	4.0
	5	78.5	31	10.8
	10	314.2	124	43

Reducing pressure losses

Pressure drops are not only introduced by filters, but also by the overall system design, in particular the length, inner diameter and layout of risers, distribution pipes, connection pipes and service pipes and each component within that system (valves, air treatment, etc.).

As stated in the section of filters, a 1 bar increase in working pressure requires some 8% more power input. Increasing the working pressure to compensate for pressure drop thus affects energy consumption and economy.

The pressure drop in the system can be minimised. The following table gives some design guidelines.

Table 54 Pressure drop in system

Pressure drop across	differential pressure
service pipes	0.03 bar
distribution pipes	0.05 bar
risers	0.02 bar
Total pressure drop across the fixed pipe installation	0.10 bar

[111] AtlasCopcoCompressedAirManual7thedition,p.103,section4.2.2

Reducing compressor pressure

Why is a certain working pressure in the system required and can it be lowered? Of course if the pressure is required to compensate for dirty (worn out) filters then these should be replaced immediately. But probably the biggest potential lies in a careful assessment of the required pressure for the various applications served by the compressor system.

Is the application requiring the highest pressure running continuously or only sporadically? In the latter case, it may be worthwhile to have the complete system run at lower working pressure continuously and install a booster compressor for those instances a higher pressure is needed.

Such interventions require a full energy audit of the compressed air system and the applications it serves, by trained professionals.

Other strategies relate to optimizing running times in multi-compressor setup, checking of condensate drains, review of piping system and replacement of filters.

Systematic approach

Energy auditors are taught to apply a systematic approach in reducing energy consumption of compressed air systems.

1. The first step is **optimising compressed air use**. The compressed air usage must be kept to the minimum. Reduction of leakage is an obvious activity, but activities should not be limited to that. Look for the best technology for a certain application. How can waste or misuse of compressed air be avoided ?
2. The second step is **optimising the pressure level and fluctuations**. Can the pressure level be reduced? Which level should be selected and what fluctuations are allowed, through application of buffer capacity or central pressure regulators?
3. The third step is **optimising the equipment and technical installations**. Can control of compressors and dryers be improved? Should a compressed air master controller be considered to optimize energy efficiency of the compressed air station? Can more efficient equipment be installed?

There is an ISO standard that describes how to perform assessments of compressed air systems: ISO 11011, Compressed air systems – Energy assessment (by ISO/TC 118), considers the entire system, from energy consumed to the resulting work performed. The assessment in accordance with ISO 11011 identifies and quantifies energy waste, balances compressed air supply and demand, energy use and total compressed air demand.

Most of the above remarks apply to industrial compressed air systems in the oil-free (and standard air) pressure range. For low pressure the remarks are essentially also applicable, but the indicative values or figures are different (leakage losses for instance).

3.4.2 Filters[112]

Ambient air drawn in by compressors may contain several contaminants and various filters are required to remove these from the compressed air stream.

An inlet filter removes particles that may damage the compressor. After the compression stages particulate filters are placed to remove particles originating from the compressor itself (from wear and tear).

Coalescing filters are used to capture oil and/or moisture that is suspended in the compressed air in very tiny droplets.

Activated carbon filters will remove odours and vapours. They are used for instance in factories where food is produced or for the production of breathing-air.

[112] http://www.air-compressor-guide.com/learn/compressed-air-systems/compressed-air-filters

As filters create a pressure drop it is important they are sized correctly and serviced (checked, emptied, replaced) regularly. Too small filters will increase the initial pressure drop. Poor servicing/maintenance will increase the pressure drop over time.

3.4.3 Dryers[113]

When air is compressed the concentration of water in a given volume increases. As air is then cooled down, this moisture will condensate and may cause problems due to water precipitation in pipes and connected equipment. For some applications the presence of water may even be damaging to the primary process, as is the case in air for paint spraying.

A drying technique can be characterised by its PDP, or pressure dew point. The PDP describes the water content in the compressed air, by indicating the temperature at which the water vapour condenses into water at the current working pressure. Low PDP values indicate small amounts of water vapour in the compressed air.

The main techniques for removing water from compressed air are:

1. After cooler
    a. This is a heat exchanger that cools the hot compressed air to precipitate water, using air or water (from a cooling circuit). The condensate is generally trapped in a water separator (can be automatically drained) and the air leaves the after cooler some 10ºC above the coolant temperature, but this can vary depending the cooler characteristics. In most cases the after cooler is incorporated in the compressor package.
2. Refrigerant dryer
    a. In this system the air passes a heat exchanger that allows a coolant to evaporate. This removes moisture from the compressed air. The coolant is then compressed and at elevated temperatures transfers part of the heat back to the compressed air stream, increasing its temperature and reducing the risk of precipitation further down the line. After expansion of the coolant, lowering its temperature, the process can start over.
3. Over-compression
    a. In this method air is compressed to a higher pressure than the intended working pressure, which means the concentration of water vapour increases. Thereafter the air is cooled and the water separated. Finally the air is allowed to expand to the working pressure and a lower PDP is attained. This method has a relatively high energy consumption.
4. Absorption drying
    a. This method involves a chemical process in which water vapour is bound to absorption material, which can be a solid or liquid. This method is unusual and involves a high consumption of absorbent materials.
5. Adsorption drying
    a. In this method water vapour is attached to hygroscopic material or desiccant (such as silica gel, activated alumina, molecular sieves). Once the desiccant is saturated it can be regenerated. Usually the system comprises two vessels, one adsorbing moisture, while the other is regenerating. The PDP that can be achieved is typically -40ºC. Adsorption drying can be characterised by the method used for regeneration:
        i. Purge regenerated (or heatless-type) dryers: Expanded compressed air is used to dry the saturated desiccant. This requires indicatively some 15-20% of the dryer's nominal capacity.

[113] http://www.airbestpractices.com/technology/air-treatmentn2/types-compressed-air-dryers-part-3-heat-compression-single-tower-deliques

ii. Heated purge regenerated dryers: The expanded air is heated by an electric air heater, limiting the purge flow to some 8% of nominal capacity. This type uses25% less energy than heatless-type dryers.

iii. blower regenerated dryers: Ambient air is blown over the saturated desiccant and no purge flow is required. This type uses less than 40% of the heatless-type dryer.

iv. Heat of compression (HOC) dryers: In HOC dryers the desiccant is regenerated by using the available heat of the compressed air. This type can achieve a PDP of -20ºC without any energy being added. A lower DPD can be attained by adding heaters. A special type of HOC dryer applies a rotating drums (divided into sectors) instead of two vessels.

6. Membrane dryers

    a. membrane dryers use the process of selective permeation of the gas components in the air. They can also be made to separate other gas components like nitrogen.

3.4.4 Heat recovery (beyond the compressor package)

As the compression process itself results in the creation of heat, the recovery of this heat can save energy if it replaces energy consumption for heat generation elsewhere in the larger system. Recovery of waste heat of compression is not difficult and requires little to no modifications to the compressor equipment itself[114].

Possible usages of waste heat are:

- process heating (preheating of processes, drying processes);
- water heating (of tap water);
- space heating (direct, as heated air, or through heating boiler return water).

Typically some 80-90% of the energy input leaves the compressor as heat. It is either available as a stream of hot air (air cooled equipment) or hot water (water cooled). The typical maximum temperatures of available heat differ per technology, pressure level and method for cooling.

Indicatively, air cooled compressors supply an cooling air flow of approximately 20 ºC above ambient (can be higher, depending on various process parameters). Water-cooled compressors supply a flow of cooling water of indicatively 90ºC (also depending on various process parameters such as the allowed temperature differential and flow rate).

A special form of heat recovery is recovery of heat for drying compressed air. In this case **regenerative desiccant dryers** can be used which operate on waste heat of a (usually oil-free, because of higher temperatures) compressor. The pressure dew point of HOC dryers can be up to -40ºC. The energy input for this dryer is minimal as HOC dryers operate without purge air losses.

When considering heat recovery the following aspects have to be kept in mind:

- The temperature difference between the source and the sink should be at minimum 5 to 10 degree K, higher is better.
- Transport distances should be minimal.
- Simultaneous supply and demand is preferred, but thermal storage is possible to overcome temporal misalignment.
- The higher the utilisation factor, the better (space heat demand is only in heating season, hot water demand is all year round)

[114] Source: http://hydraulicspneumatics.com/air-compressors/compressed-air-may-be-more-efficient-you-think?page=2

If the compressed air is used as source for heat, the pressure may be reduced because of the pressure loss in the heat exchanger. This may be some 0.02 to 0.03 kW per mbar extra pressure loss.

3.4.5 Oil-free versus oil-injected

As stated in Task 1, oil-free air (defined as Class 1 according ISO 8573-1) can be produced by oil-free equipment but also by oil-lubricated equipment ('standard air') combined with proper air treatment for removing oil. The latter has been and, for a certain share of customers, still is standard practice in food & beverage companies, hospitals, etc.

However, the two technologies are not comparable or offer similar functionality at product package level. In order for oil-lubricated equipment to supply air that meets Class 1 according ISO 8573-1, filtration and separation has to be applied. In most applications, this is a matter dealt with a system level, beyond the product package boundaries.

In Task 1 it is argued that comparing performances at compressed air system (CAS) is not advised as:

- each CAS is often unique to a specific installation;
- each CAS may include equipment from several different manufacturers, with different functions, put on the market at different times; and
- a single CAS can include several different compressors, of different types, which may all have different full-load operating pressures.

Comparing at CAS level requires the consultants to establish a methodology for establishing a reasonable basis for comparison (system size?), assessment of losses (from packages, filters, separators, other equipment like drying equipment which is also affected by the choice for lubricated or oil-free) and to assess what certification, compliance, or enforcement practices would be required for a large variety of system designs, and potential waiver criteria[115].

The functionality of lubricated vs. oil-free at package level is not the same, as for certain compressed air customers the risk of presence of oil in their system is acceptable, whereas other customers will do anything to avoid this. So the technological solution partly determines the application, which means they offer a different functionality (at package level).

The (simplified) assessment below shows some elements that need to be considered when comparing oil-free with oil-lubricated + air treatment.

Table 55 Simplified assessment of 'oil-lubricated with oil removal' vs 'oil-free'

	oil-lubricated with oil removal	**oil-free**
Need for oil-filters	oil-separator and filter within package oil-filter further up in the compressed air line use of filters results in pressure loss (increases when in use)	no need for oil-filters in the compressed air line depends on intake air quality, no associated pressure loss
Purchase costs of compressor package	lower	higher, but purchase is typically less than 10% of overall cost-of-ownership possibly higher refurbishment

[115] These are also the arguments put forward by DOE to not look at system level, but instead focus on the package only.

		costs
Service costs	costs of oil-filter costs for water-oil separator (before discharging water to environment)	
Energy costs	is related to efficiency and working air pressure required increased pressure loss can increase energy costs for the same package but the compression process can have a different compression efficiency	working air pressure is lower, can result in lower energy costs for the same package but the compression process can have a different compression efficiency
Other benefits	heatless dryers require 15-20% air capacity for purge air blower purge requires still some 10% of capacity	can use heat-of-compression dryers, drastically reducing energy loss from drying

Some 'Process' and 'instrument' air applications require an oil content less than 10 parts per million. As almost all oily contaminants are present as extremely small droplets (less than 1 micron), mechanical filtration may be insufficient; adsorption equipment can efficiently remove the oil.

3.4.6 Alternatives to compressed air

In accordance with the methodology required for this study, this section explores alternatives to 'compressed air' as part of a functional systems approach.

The reason most customers opt for compressed air systems is that they offer (a) unique (combination of) benefits when compared to hydraulic, electrical or mechanical systems[116]:

- easy to store and to transport (also over long distances, no recirculation necessary);
- clean and dry medium;
- safe to operate;
- components of the system are often less expensive, more robust/simpler, lighter and easier to maintain (e.g. no exchange of fluids necessary);
- fast medium;
- overload normally causes no problem;
- parameters infinitely variable.

For a vast number of applications, the use of compressed air is therefore a very attractive alternative.

However, section 3.4 also showed that compressed air is sometimes used in applications which are not optimal from energy point of view, where benefits of compressed air are not decisive and alternative systems exist. The table below shows certain compressed air uses, which may be better served by alternative systems (not exhaustive!).

[116] Advantages based on Bierbaum and Hutter, 2004, as referenced in "Energy Efficiency in Manufacturing Systems", p.25. [Note: applies to 'standard air' only]

Figure 22 Alternative applications to compressed air end uses[117]

Existing compressed air end use	Potential Alternatives	Reasoning
Open blowing, mixing	Fans, blower, mixers, nozzles	Open-blowing applications waste compressed air. For existing open-blowing applications, high efficiency nozzles could be applied, or if high-pressure air isn't needed, consider a blower or a fan. Mechanical methods of mixing typically use less energy than compressed air.
Personnel cooling	Fans, air conditioning	Using compressed air for personnel cooling is not only expensive, but can also be hazardous. Additional fans or an HVAC upgrade should be considered instead.
Parts cleaning	Brushes, blowers, vacuum pumps	Low-pressure blowers, electric fans, brooms, and high-efficiency nozzles are more efficient for parts cleaning than using compressed air to accomplish such tasks.
Air motors and air pumps	Electric motors, mechanical pumps	The tasks performed by air motors can usually be done more efficiently by an electric motor except in environments with special requirements.

The simple analysis shows that certain functions of compressed air can be provided by products that are, or may be, regulated under the Ecodesign Directive, notably fans (for air displacement, cooling) and electric motors (for torque, movement).

The question then arises whether the scope should be widened to allow an analysis per function (e.g. personnel cooling) between compressed air versus fans, air conditioning or electric motors.

Virtually all compressed air system handbooks and literature already discourage illegitimate use of compressed air (such as for personnel cooling or certain forms of parts cleaning) so the problem is not that a better alternative exists, but that this misuse has to be stopped immediately through better education of personnel and plant operators.

But there are applications where indeed the use of compressed air, for instance for moving, clamping, gripping, holding may be better served by other technologies, such as electric motors. This however requires a thorough assessment of the specific application and the functionalities required, at a system level.

An example is the study "Planning the efficient use of compressed air in the body shop"[118] which compares pneumatics as drive technology versus electric motors. The study shows that, with careful implementation, pneumatics should not be dismissed upfront, especially considering the total cost of ownership.

An analysis of all compressed air applications and comparing these two alternatives is however vastly outside the scope of this study and not proportional to its goal (to discuss product policy options for low pressure and oil-free compressor packages).

3.5 End-of-Life

This section focuses on end-of-life aspects of compressor packages (not specifically limited to low pressure and oil-free). It addresses:

- Repair- and maintenance practice (frequency, spare parts, transportation and other impact parameters);
- Collection rates, by fraction (consumer perspective);
- Estimated second hand use, fraction of total and estimated second product life (in practice);

[117] Based on: Energy tips compressed air (tip sheet #11, August 2004, Industrial Technologies program).

[118] https://www.festo.com/net/cs_cz/SupportPortal/Downloads/346345

- Best Practice in sustainable product use, amongst others regarding the items above.

The use of the products is described in section 3.3.

3.5.1 Maintenance and repair

Especially moving parts are subject to wear and tear and will require replacement if the performance goes beyond acceptable limits. If repair becomes too costly, or the performance of repaired or refurbished equipment is too low when compared to new equipment, the product will be discarded.

Servicing and/or maintenance

Servicing and/or maintenance means the regular check and/or replacement of parts or components of the machine, ending with the machine resetting to the design operating conditions. It covers replacement of air (and other) filters, worn out gaskets and/or seals, bearings, and oil (if used in coupling or timing gear), etc.

Servicing and/or maintenance are predictable actions and is usually part of the sales contract with the supplier of the equipment.

In the environmental analysis (Task 5) the material input for maintenance (apart from identified consumables) **and** repair together is taken into account as 1% of the initial material input. Air filter material is included in that assessment as consumables.

Repair

Repair means solving an immediate problem and any action to identify the cause of failure, after an incidence has occurred (like a foreign object entering the compression chamber or a coupling failure, drive shaft failure, seizure, valve failure, etc.) or is imminent (as judged from monitoring of equipment parameters). The damaged parts will be replaced with new, identical parts.

The material input for repair is estimated to be covered by the 1% allocated to maintenance.

Reconditioning

Reconditioning us a related term and in this context means a combination of cleaning, maintenance and minor repair, most often for the purpose of reselling the product. The difference (as defined in this study) is that with refurbishment the goal is to have the refurbished part or product back to "as new" conditions. Reconditioning may be that some loss of performance is accepted because of the age of the product, but still functioning properly.

Refurbishment and/or remanufacturing

Refurbishment and/or remanufacturing means a combination of cleaning, extensive maintenance and/or repair for the purpose of restoring the performance of product to 'as new' conditions, often with a guarantee. Refurbishment can apply to essential parts of the package (such as remanufacturing the air-end, for the same owner) but can also apply at the package as a whole (often for the purpose of reselling).

Where repair is focused on solving an immediate or imminent problem, refurbishment is focused on restoring or improving upon the original performance, and often involves replacing core components such as the air-end, electric motor, plus critical components such as (safety) valves etc., even if the components themselves have not (yet) failed. After reassembly according manufacturer standards the part or package is tested to ensure quality.

It may even be that repair leads to refurbishment; e.g. in the case of bearing failure(s) the air-end has to be opened up, and depending on rotor conditions, the complete air-end may end up being refurbished.

Many manufacturers (such as, but not limited to, Atlas Copco[119], Ingersoll Rand[120], Sullair[121]) offer refurbished (or reconditioned, remanufactured) equipment, possibly accompanied by a

[119] http://www.atlascopco.com/usedequipmentus/industrialequipment/

buy-back program of old equipment. In addition to these, there are numerous (servicing) companies, not OEM manufacturers, who refurbish parts or components using OEM or other parts.

Whether or not refurbishment extends the product life to beyond what is indicated in Task 2 as 'product life' remains unclear. Manufacturers have indicated refurbishment intervals shorter than product life, indicating a periodic need for this activity several times during product life. But those same activities can also be deployed to extend the product life.

For larger equipment (e.g. > 75kW) the motor life exceeds the life indicated for the package (see section below, on 'Component life'). It is however not known how many refurbishments with the intention to extend product life take place annually, and - if they do – whether the refurbished product is then used within the EU or exported. This aspect could therefore not be quantified.

Costs of refurbishment during product life have been stated in Task 2.

Component life

Compressor packages are complex products with many parts, each having a different service life or technical life.

The average product life of the entire package has been estimated by industry experts to be almost 9 years for ZFCR products to almost 13 years for Oil-free products. During this life replacement of main components such as air ends, motors and bearings may have taken place (see also "refurbishment").

In the Lot 30 report on electric motors[122] is stated that "small motors are normally not repaired and are replaced upon failure. Medium power induction motors above 11 kW are normally repaired at least 2 times during their lifetime but this can occur up to 4 times."

The shortest life is most likely found for inlet filters and water separators, which require periodic replacement or emptying. The part with the longest life is probably the frame or skid onto which the components are placed.

The life of main components are:

Table 56 Average life of main components

Air end [3] **(years)**	**Bearing** L_{10} (hours) [2]	**Electric motor** [1] Nominal power	(years)
can be after 5 to 8 years, **or 30% to 50% of product life**	minimum: 25 000 maximum: depends on design/application indicative 100 000	1.0 – 7.5 kW	12
		7.5 – 75 kW	15
		75 – 250 kW	20

Notes:

[1]: Average life of induction motors, including repair. 75% of induction motors fail due to worn bearings, with stator failure being the other major cause of failure. Source: A. de Almeide et al, "EuP Lot 30: Electric Motors and Drives, Task 3: Consumer Behaviour and Local Infrastructure", contract ENER/C3/413-2010, Final, April 2014.

[2]: Bearing life expressed as L_{10} corresponds to a 10% cumulative failure, and is given in hours. Bearing performance is extremely important as bearing axial and radial clearance influence rotor clearance

[120] http://www.ingersollrandproducts.com/am-en/products/air/services/remanufacturing-services

[121] http://www.sullair.com/americas/en/parts/reman-air-end-exchange

[122] Anibal de Almeida et al, "Electric Motors and Drives, Task 2: Economic and Market Analysis", ENER/C3/413-2010, Final, April 2014.

(means that bearing failure may lead to rotor failure). The values stated are indicative and sourced from technical literature.

3: The actual life of an air-end will vary considerably depending on the technology type and the operating conditions, in particular the pressure range in which it operates. The table shows a general indication of what can be considered as 'average' air-end life and specific technologies may deviate considerably from this 'average'.

If the replacement or renewal of parts or components is planned, it is labelled "maintenance" (such as filter replacement, oil change, checking of tolerances). If it is unexpected, it is labelled "repair". If it is planned and involves a major upheaval and/or change of ownership, it is labelled "refurbishment".

3.5.2 End-of-life

The product reaches its end-of-life when the use-phase stops and the product is discarded. Refurbishment (and other forms of product life extension) are covered through the use-phase.

Determining the impacts during the end-of-life are the collection rates and subsequent treatment, including recovery or recycling rates.

Collection rates

The assessment in Task 1 regarding the applicability of WEEE and ROHS led to the conclusion that (LP and OF) compressors are probably excluded from these Directives as they can be considered "large-scale stationary industrial tools". Therefore there is no mandatory producer responsibility to take back discarded products (waste) or pay for proper treatment.

Many manufacturers however already have programs in place to extend product life and facilitate disposal (see "refurbishment" above).

Once the product has reached the end of its technical life, and the product is not returned to the manufacturer for refurbishment, product disposal is most often left to the owner’s discretion. It can be assumed that most EU users of compressors displace of their products through appropriate channels (mainly scrap metal dealers) after the economic life has been reached because of the residual scrap value (close to 0.27 EUR/kg of product, not considering costs for transport dismantling, material separation etc. – see also section 2.5.3).

Landfill is not considered the default waste route, because of this scrap value. As over 80% of the material composition of electric driven compressors are metals (mostly steel, but also aluminium and copper) it can be assumed that these materials will enter the metals recycling loops. The collection rate for the product is therefore assumed to be high.

In most recycling facilities it is commonplace that major non-ferrous fractions (e.g. the electric motors and wiring that contain a high copper content) are separated from ferrous fractions and send to separate disposal routes as they should be, as otherwise the (precious and/or non-Ferro) metal content is 'lost' in generic metal recycling routes[123].

When expressed as EOL-RR (end-of-life recycling rate, defined as the quantity post-consumer metal fed into the scrap market divided by the quantity collected) the value for ferrous metals is between 70-90%, for copper it is 43-53% and for aluminium it is 42-70% (variations depending on reference used, all values taken from Recycling Rates of metals – a status report, UNEP 2011[124])

Electronics are assumed to be dismantled and send to specialist electronics recyclers as these also represent economic value (presence of precious metals). EOL-RR are presented in the UNEP report as well.

Despite high expected recycling rates of metals, it can be assumed that certain materials (critical raw materials) are 'lost' due to inadequate recycling facilities and or activities (Beryllium

[123] See also http://www.bir.org/industry/non-ferrous-metals/

[124] Recycling rates of Metals – a status report, UNEP, 2011.

for instance, is applied in copper alloys, but during recycling often is diluted or ends up in slag) or simply metallurgical processes. This problem is however not limited to compressor waste.

The plastics fraction (on weight basis) in compressors is small compared to the overall weight and the scrap value is less than steel etc. If the plastic is easily removable, the chance that the material (or the embodied energy) is recovered increases. But it may be that plastics wilfully end up in blast furnace steel production as it is used as reductant, replacing the use of coke. The gasification of the (waste) plastic and the introduction of the syngas in the blast furnace could help reduce CO_2 emissions of steel production[125].

Estimated second hand use

No data was found for second hand use (extension of product life, including refurbishment, beyond the technical life of the package as indicated) inside or outside the EU. It has been established that refurbishment is common practice but it has not been possible to locate data that quantifies the amount or level of second hand-use, within or outside the EU.

3.5.3 Best practice in sustainable product use

Compressors for low pressure and or oil-free air are no household items. They run in commercial/industrial facilities and require a major investment. The operating costs (including energy and maintenance) are generally multiple times the purchase costs.

Nonetheless the US survey of compressed air suppliers and users showed that most operators lack education as regards how to realise energy saving measures.

The most significant energy savings are however to be achieved beyond the compressor package boundaries and relate to applying heat recovery, optimising system pressure, avoiding misuse of compressed air, reducing air leakage, etc.

Within compressor package boundaries the control of compressor operation is important, where operators should avoid throttling the equipment, in preference of applying speed control or inlet/outlet guide vanes (in case of turbo compressors).

Energy saving measures can differ in rate of return. The best practice in sustainable product use would be applying energy saving measures that have a rate of return within the technical product life, not confined to 1 or max. 3 years as is often the case.

3.6 Local Infra-structure

The section reports on barriers and opportunities relating to the local infra-structure. According the MEErP methodology this section must cover the reliability, availability and nature of the energy form involved, and other infrastructural items such as communication networks (e.g. hot spots, WLAN, etc.), installation, e.g. availability and level of know-how/training of installers and other aspects of the physical environment, as these may form barriers to the introduction of more efficient equipment.

Technical infrastructure

The study did not identify technical barriers for users, related to availability of electricity (the energy form involved) or other infrastructure related to water, telecommunication.

What is relevant as barrier or opportunity is the physical environment especially in relation to heat recovery options. If there is no need for low-grade heat, options for heat recovery are reduced.

---

[125] CO2 MITIGATION FOR STEELMAKING USING CHARCOAL AND PLASTICS WASTES AS REDUCING AGENTS AND SECONDARY RAW MATERIALS, F. Hanrot, D.Sert, J. Delinchant, R. Pietruck; T. Bürgler, A. Babich, M. Fernández,R. Alvarez and M.A. Diez, 1st Spanish National Conference on Advances in Materials Recycling and Eco – Energy Madrid, 12-13 November 2009.

Also related to the technical infrastructure, but not a barrier, is that oil-free equipment, and low pressure equipment that is not oil lubricated, does not require an oil-water separator before discharging water removed from the compressed air to the mains sewage.

Non-technical infrastructure (cognitive, financial)

There may be cognitive barriers as specifiers and users are unaware of the ratio between purchase costs and operating costs of the installation considered, often overestimating the importance of the first.

There may be financial barriers (for instance access to capital to fund investment in more efficient equipment) as users apparently apply very high discount rates (meaning that the technology option must have a very high payback rate in order to be of interest).

A US study[126] stated that over 75% of suppliers offer some kind of system energy efficiency services, and some 50% also offer end-use analyses and leak (detection) services. Producing revenues for these services is not the main reason for offering such services. As more firms offer efficiency services increasing, the main motivation for suppliers is customer retention.

Some 10% of all participants reported that efficiency-oriented services such as leak detection, energy-use monitoring, or assessment of control strategies were included in the service contract.

Most suppliers identified customers' lack of understanding of the benefits of compressed air efficiency measures as the major barrier to their increased sale. Compressed air efficiency consultants have similar experiences. It appears that most clients rely on in-house staff for implementation of compressed air efficiency measures.

The same study confirmed the observation that customers are largely in the dark about the nature of compressed air system efficiency measures and maintenance practices as only 9% of customers interviewed for the program identified controlling energy costs as the primary objective in compressed air system maintenance and management. Only 17% mentioned efficiency at all as a system management objective. And 75% of system operators had no formal training in compressed air system efficiency.

Ensuring adequate air supply is the main concern for customers, and as many customers have experienced serious problems in compressed air system operation and maintenance (35% had experienced an unscheduled shutdown, excess moisture and inadequate air pressure were the most frequently reported problems), concern about operating consistency provides an effective route to selling efficiency-oriented services.

[126] "Assessment of the Market for Compressed Air Efficiency Services" prepared for OakRidge National Laboratory and Lawrence Berkeley National Laboratory by XENERGY,Inc. Burlington, Massachusetts, DOE/GO-102001-1197 June 2001

TASK 4: Technologies

4 Technologies

4.1 Introduction

In this Task 4 the technologies applied in low pressure and oil-free compressor packages are described, illustrated with data on the performance of the average product, 'best available' and 'best not yet available technology'.

Secondly, this task describes inputs for a (streamlined) life cycle assessment, covering production, distribution, use and end-of-life.

4.2 Technologies per application range

Task 3 'Users' showed the compressor technologies for the application ranges considered.

Table 57 Technologies per application range

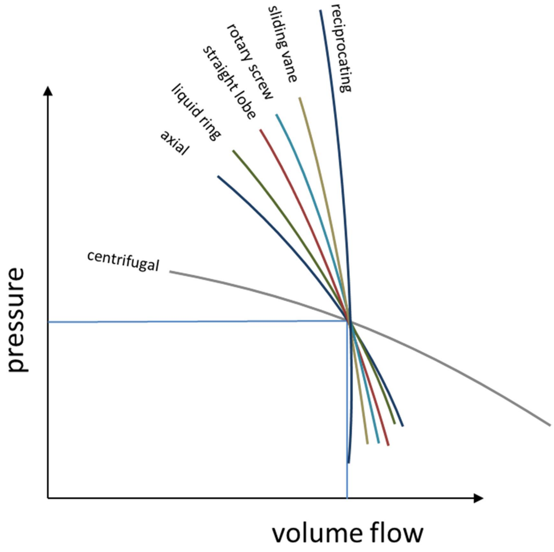
Main type	sub-type	sub sub-type	Low-pressure (1.1 – 3.5 bar(a))	Oil-free (7-15(bar(a))
pos. displ.	reciprocating	piston		✓
	rotary	lobe ("Roots blower")	✓	
		screw	✓ ("screw blower")	✓ (incl. water inj.)
		vane	✓	
		scroll		✓
		tooth (also 'claw')	✓	✓
		liq.ring	✓	
dynamic	axial	axial	(not applied)	(not applied)
	centrifugal	single stage	✓	
		multi stage / in-line	✓	
		multi stage / multi axis		✓
		side channel	✓	

When plotting the performance of various compressor technologies in a single diagram **(ignoring the differences in actual volume flows delivered or pressure ratios achieved and ignoring effects of speed control)** the differences in (single speed) curves are indicative of the behaviour of the compressor. Like any other fluid mechanic device, the curve will be a slope, with the general inclination of the slope showing how pressure and volume flow interact.

The figure shows that in general the volume flow rate produced by turbo compressors is more susceptible to change with changing discharge pressure, whereas for positive displacement machines the volume flow changes only slightly with changing discharge pressure[127]. Such basic behaviour is relevant when deciding for a combination of technology and application.

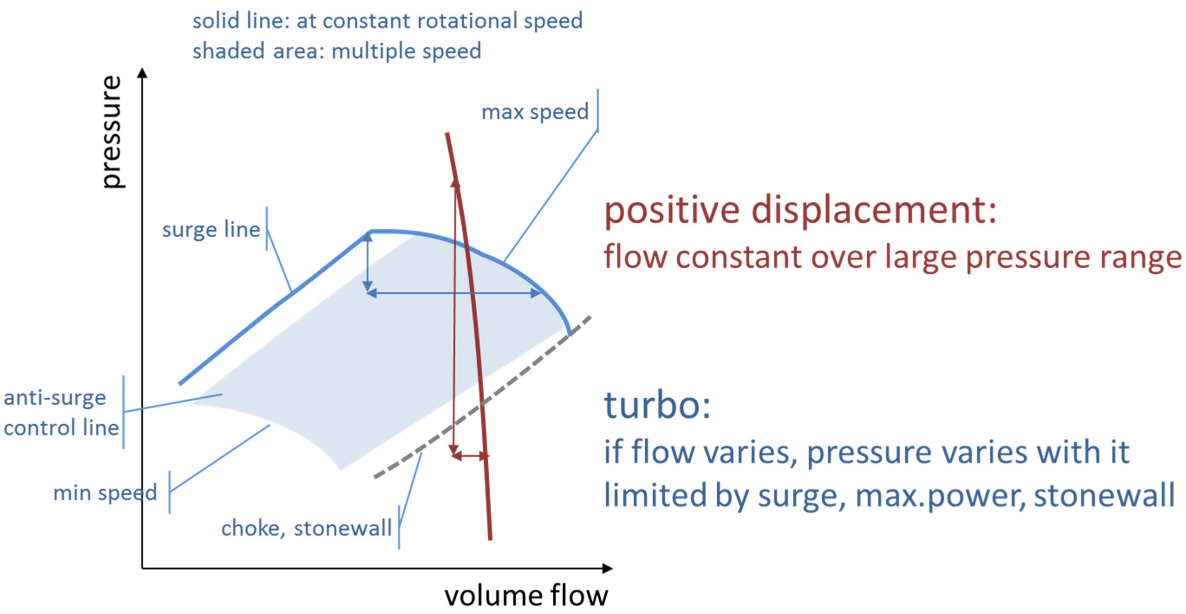
[127] Of course several options (like changing the speed) can help to maintain discharge pressure at varying volume flows.

Figure 23 Comparison of pressure vs volume flow curves of compressor technologies (rescaled to allow comparison, based on single speed)[128]



The figure above is to indicate typical differences in flow-pressure curves of various technologies and says nothing about the performance of a specific technology at a specific point.

Figure 24 Pressure vs volume flow curves of typical turbo versus positive displacement machine (rescaled, simplified, not indicative for energy efficiency) [129]



The following sections describe per technology the general principles, performances, control options, etc.

[128] Based on: http://www.pipingguide.net/2009/12/compressors-and-compressed-air-system.html

[129] Based on: http://www.pipingguide.net/2009/12/compressors-and-compressed-air-system.html

4.3 Positive displacement compressors

4.3.1 General

In a positive displacement ('volumetric') compressor the air is contained in the compression chamber and then mechanically reduced in volume to raise the pressure. The temperature raises as a consequence of that.

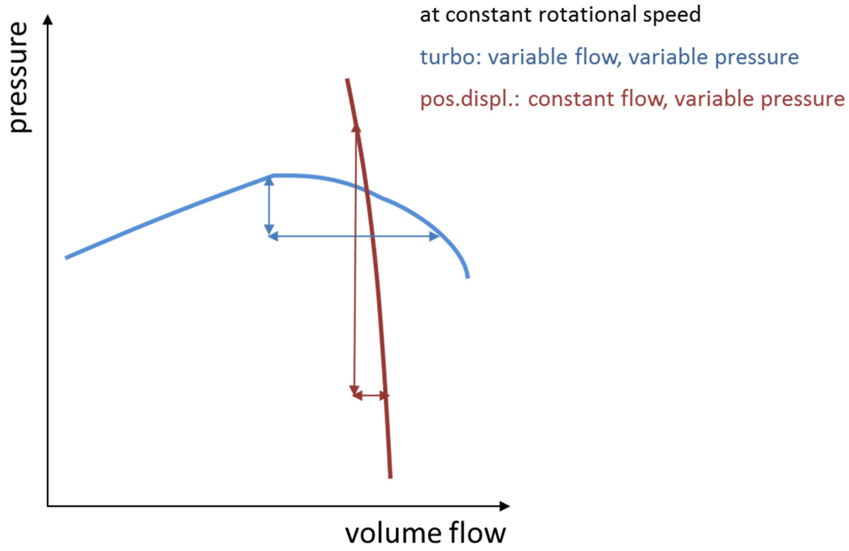
The required power is mostly determined by the desired flow, but also affected by the discharge pressure, but not as much as with turbo compressors.

Positive displacement compressors do not have a surge-limit and are in general better suited for, or easier to control in case of, fluctuating conditions (changes in inlet pressure, discharge pressure, inlet temperature, etc.) or for large flow control range applications.

Inlet pressure, volume flow, and pressure ratio are important variables that influence the power consumption in positive displacement compressors.

The following sections describe various types of positive displacement compressors as applied in the low pressure and oil-free application ranges.

Figure 25 Performance curve of positive displacement versus centrifugal compressor



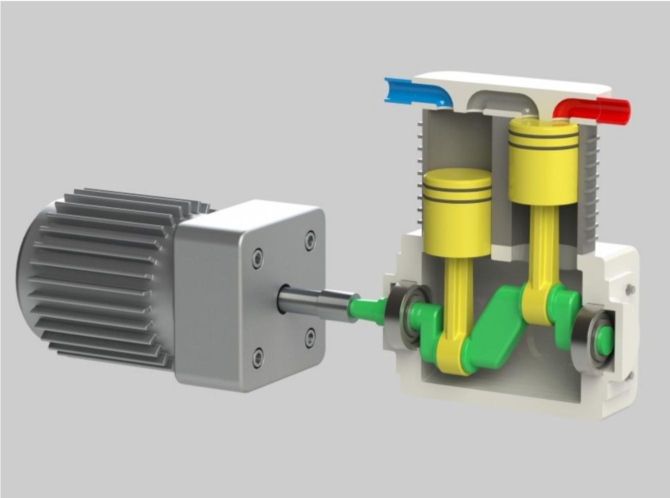
4.3.2 Piston compressors

The piston compressor belongs to the family of reciprocating positive displacement compressors. They are relevant in the oil-free application range with an operating range between 7 to 15 bar(a) and are virtually not present in the low pressure application range as defined in this study [130]. Discharge pressures below 3.5 to 5 bar(a) are generally too low for applying reciprocating technology.

The basic working principle is a piston compressing air in an enclosed cylinder, with valves regulating admission and discharge of air.

Oil-free piston compressors have piston rings of PTFE ("Teflon®") or carbon, alternatively the piston and cylinder wall can be toothed as on labyrinth seals of compressors. Larger machines are equipped with a crosshead and seals on the gudgeon pins, and a ventilated intermediate piece to prevent oil from being transferred from the crankcase and into the compression chamber. Smaller compressors often have a crankcase with 'sealed for life' bearings.

Figure 26 Basic working principle of piston compressor (depicted: 2-stage)



The above figure is illustrative only and does not depict a real working machine.

Diaphragm compressors

Within the group of reciprocating positive displacement compressors there are also diaphragm compressors. The diaphragm is actuated mechanically or hydraulically. The mechanical diaphragm compressors are used for a small flow and low pressure or as vacuum pumps. The hydraulic diaphragm compressors are used for higher pressures.

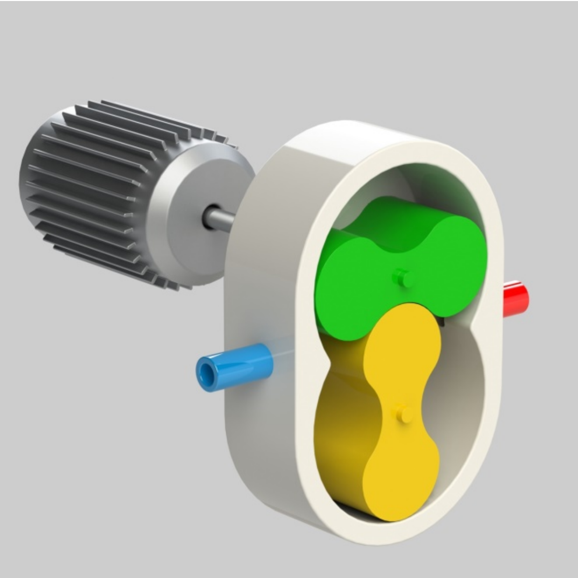
As diaphragm compressors are rarely used for low pressure (< 5 bar(a)) or oil-free applications (between 7-15 bar(a)) **they are not considered any further**.

[130]Some manufacturers call the range between 7-16 bar "low pressure". Source: http://www.afcompressors.com/solutions-products/low-pressure-compressors/

4.3.3 Lobe compressors

Lobe compressors (also known as "Roots blowers" or lobe blowers) are rotary positive displacement compressors that utilize external compression which means there is no internal compression in the compression chamber. They have two impellers with an inlet directly opposite the discharge port. As one impeller begins to seal off the air inlet, air is trapped between the blower case and the impeller. Meanwhile, the other rotor begins to open at the outlet and is pressurized by the system back pressure. The impeller sweeps the trapped air to the discharge port where it passes the volume on to the system.

Figure 27 Working principle of lobe compressor



The above figure is illustrative only and does not depict a real working machine.

The rotary lobe compressors deliver an amount of air directly in proportion to rotational speed. The input power is largely dependent on the total pressure across the machine. The suction and discharge pressures are determined by the system conditions. The temperature rise of the discharge air largely depends on the differential pressure across the device. The volume flow is proportional to rotational speed. Changes in air density have no effect on volume flow.

The lobe blower is an "oil-free" design: The lobes do not touch and are positioned through a gear. No oil is injected in the chambers. As there is a minimal clearance between the lobes, the pressure differential is limited. If the blower is used beyond the specified operating conditions the temperature of the compressed air/gas can increase so that the lobes expand to a point they touch the compression chamber walls.

Lobe compressors exhibit their best efficiency at moderate compression ratios, between 1.1 to 2. At higher pressure ratios the lack of internal compression results in increasingly reduced energy efficiency. However the smaller the pressure ratio, the smaller the difference is to other positive displacement compressors.

The original design consists of two straight lobes with noticeable pulsation noise and turbulence as the blower 'pumps' air in discrete pulses. This requires dampening of sound, which creates a pressure loss. The 3-lobe design (by a few manufacturers) offers lower pulsations, and the helical ("twisted") lobe (shape quite similar to screw compressors, however without internal compression) helped reduce noise emissions and pulsations even further. Lobe compressors are typically belt driven.

Ideally, the lobe compressor is capable of resisting high pressures but the mechanical limitations, increased power intake, temperature rise and increased clearance losses restrict the working pressure head to about 1 bar(g) for air cooled blowers in single stage operation.

The operating envelope for this technology is between some 10 m^3/h to 10,000 m^3/h for pressures from several hundred mbar to 1 bar(g) in single stage construction.

Lobe compressors find their way in applications such as:

- Pneumatic conveying: Vacuum, pressure and combination conveying of cereals, cement, husk, baggage, granules, powders and other similar material the best performance;
- Effluent treatment plants: For diffused aeration and agitation of effluent;
- Water treatment plants: For backwashing of filter beds/basins;
- Aquaculture: For maintaining the dissolved oxygen level;
- Cement plants: For blending, aeration, fluidisation and conveying;
- Slurry agitation: For maintaining the B.O.D. / C.O.D;
- Biogas boosting: Transferring of biogas from gasholder to boiler;
- Flocculation: To increase the removal of suspended solids in primary setting facility;
- Chemical plants: For supplying of process air;
- Electroplating plants: For oil free air agitation of electrolyte to maintain uniform density;
- Paper plants: For coating of paper or knife edge;
- Yarn drying: Vacuum or pressure drying of yarn;
- Polyester chip conveying and drying: For transfer of polyester chips;
- Reverse jet filters: For reverse cleaning of filter bags.

For many years the lobe blower was used in WWT aeration as they can supply a wide range in flow and withstand frequent start-stops. The product offering is vast and growing as new lobe geometry is introduced over time (from two-lobe to tri-lobe, to helical lobes).

However, in recent years several competing technologies have entered the market, such as screw blowers and turbo compressors with high speed drives and (recently) Blade® compressors, which offer advantages as regards package efficiency, noise, maintenance, etc.

4.3.4 Screw compressors

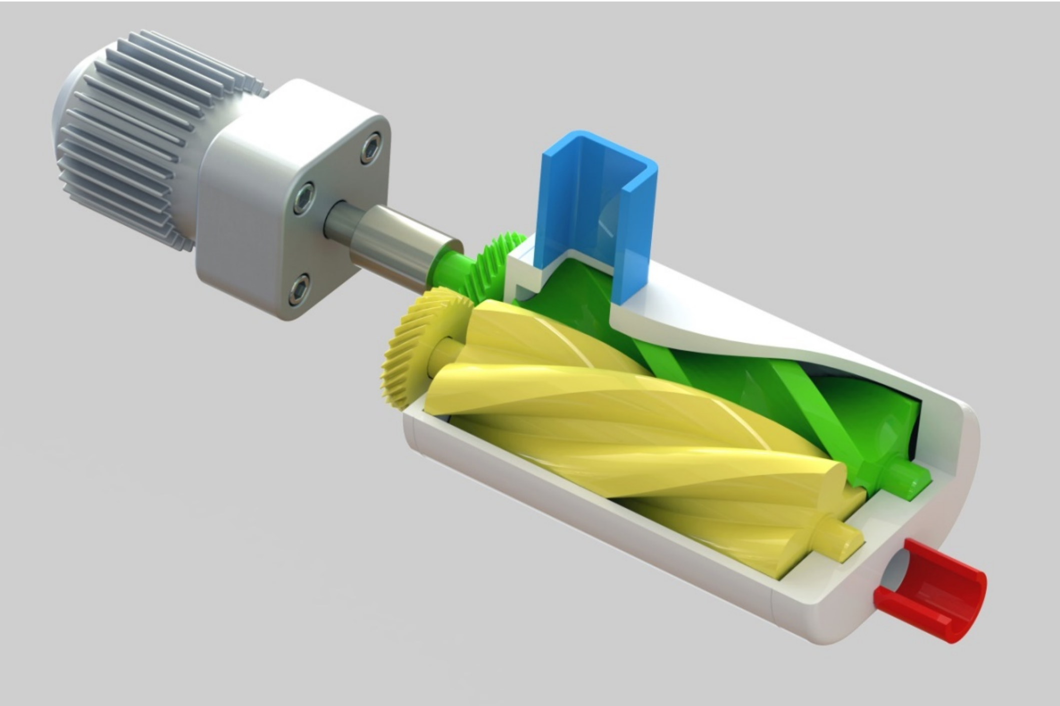
The oldest "screw" compressor patent application is probably from 1878, by Heinrich Krigar from Germany (patent DE 4121, 1878 "Schraubengebläse" and patent DE 7116, 1878 "Verwendung eines Schraubengebläses als Gebläse, Pumpe, Presse, Motor und Messapparat") but it wasn't until 1920-1930 that cycloid profiles could be produced with reasonable economy of production. Most applications were related to pumping.

The first "modern day" screw compressor patent application dates from 1938, by Alf Lysholm from Svenska Rotor Maskiner (SRM), and the technology was licensed to many companies such as Howden (1946), Aerzener (1950) and Atlas Copco (1954)[131], who further developed it in 1955 (by Patrik Danielsson and Alf Lysholm) and 1958 (Iwan Akerman) and in 1967 (Ivar Trulsson)[132] [133] [134].

The main principle of the screw compressor, a helical rotor, can be applied to a single screw (with two side gate or star rotors) [135], a twin screw (this is the most common configuration) and even three rotor screws (see section 4.7.4).

The helical twist of the twin rotors compresses air as it is transported to the discharge port.

Figure 28 Screw compressor – illustration of working principle[136]



The above figure is illustrative only and does not depict a real working machine

[131] http://opconenergysystem.com/wp-content/uploads/2015/11/The-History-of-SRM.pdf

[132] http://atlascopco.industrialtechnique.com/en/history-of-atlas-copco/

[133] http://www.atlascopco.com/history/evolution/products/compresstech/

[134] http://www.ritchiewiki.com/wiki/index.php/Air_Compressor

[135] There are two single screw manufacturers in the world: Vilter Manufacturing Inc. from USA and J&E Hall from UK [http://www.argesas.com/en/teknolojiler.php?teknoloji=48] and it appears these designs are more common for refrigeration applications and for this reason will not be dealt with any further.

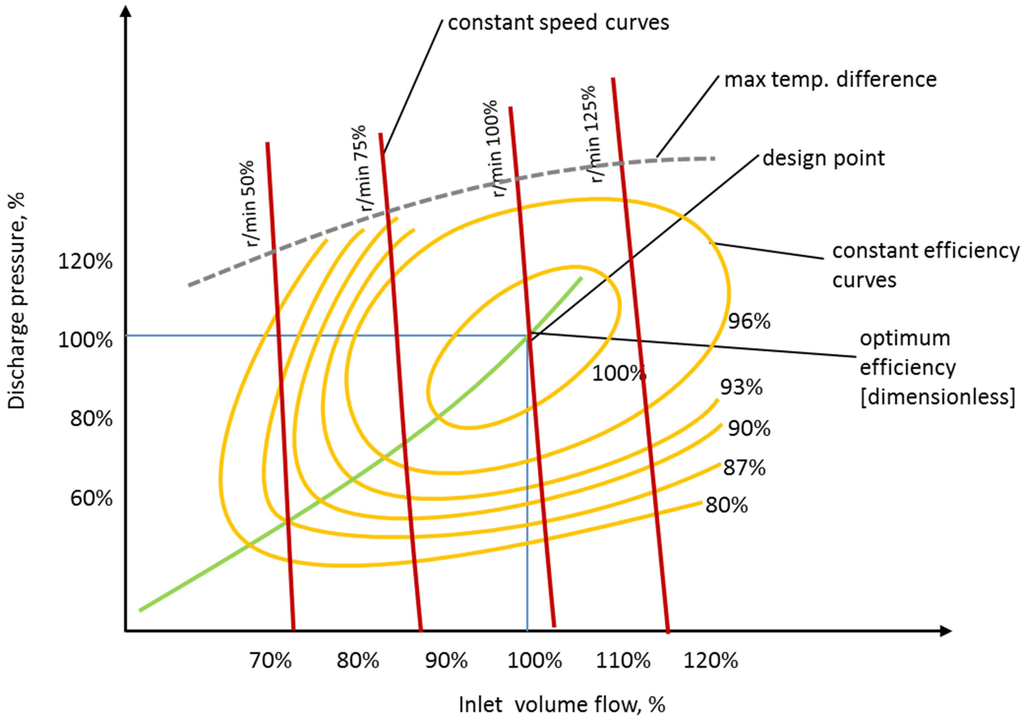
[136] This figure is for the illustration of the basic working principle only, and may contain placing, sizing of components different to 'real' products for the purpose of showing the working principle. It is not intended as a realistic rendering of actual product configurations, as available on the market.

Unlike oil-injected screw type compressors the rotors in 'oil-free' low pressure screw compressors do not touch. The geometry is such that clearances are kept minimal and maintained by a synchronizing gear. A gear box may be added for achieving a certain rotor speed with respect to motor speed. The gears are lubricated, but seals prevent the oil to enter the compression chamber.

The figure below shows a typical volume flow versus pressure diagram, however for a multiple speed compressor. The red lines show the pressure/volume flow operating points for various speeds, showing a near vertical. This means that the screw compressor can produce against a range of discharge pressures, while volume flow remains relatively unaffected. Multiple speed operation expands the volume flow range.

At the top the speed curves are limited by the maximum allowable temperature increase. The optimum efficiency (yellow constant efficiency curves) is achieved in a single operating point and drops off when operating further away from this point.

Figure 29 Typical performance curves of (screw type) positive displacement compressor (variable speed)[137]



For screw compressors the volume flow has, by 1st order approximation only, a linear relation to rpm. The discharge pressure has only a limited influence on volume flow.

The volume flow and power consumption grow almost linear with compressor speed, at constant discharge pressure.

This means that with 50% of 'nominal' speed, the volume flow is 50% of 'nominal' flow and the power is 50% of 'nominal' power.

The achievable pressure ratio per compressor stage does not depend on molecular weight but is limited mostly by the allowable gas discharge temperature or by mechanical limits.

Depending on the discharge pressure the screw blower may have various rotor configurations. Certain manufacturers apply a "3+4" (male/female rotor) configuration for up to 2 bar(g) and a

[137] All values (volume flow, pressure and efficiency) are expressed as dimensionless values.

"4+6" configuration (male/female rotor) for up to 3.5 bar(g). Manufacturers also offer a variety of port designs to further adapt the compressor to the final application.

The following sections describes the three variants of (twin rotor) screw compressors relevant for low pressure (screw blowers and oil-free screw compressors) and oil-free applications (oil-free screw compressors and water injected screw compressors).

Screw blowers

Low pressure screw type compressors designed for maximum 1 bar(g) are also referred to as "screw blowers".

As opposed to standard 7-10 barg pressure screw compressors (which have been on the market for some 40 years already), the rotors in screw blowers are relatively longer and thinner, as the forces acting upon the screws are lower. The internal pressure ratio is adapted to low pressure operation and cooling is simpler.

Screw blowers entered the market for low pressure applications fairly recently (some 5 to 10 years ago) and offer advantages in improved efficiencies compared to other typical low pressure technologies that do not have internal compression, such as lobe blowers.

Additionally, screw blowers have a flatter performance curve, across a wider range of operation, compared to lobe blowers. Lobe and other types of blowers are typically less efficient at the extremes of their operating range [138].

The power consumption is a non-linear function of discharge pressure. For a small built-in volume ratio, the relation is quite steep. This applies more to lower pressure applications which use a lower built-in volume ratio. Compressors with a higher built-in volume ratio, show a more flat response, or increase in power consumption with increase in pressure. This applies more typically to high pressure applications.

Standard oil-free screw

Screw compressors for oil-free applications, or low pressure above 1 bar(g), are also referred to as 'dry running screws'. As there is no oil to seal the gap between rotors and stator, clearances have to be tighter in order to maintain higher efficiencies. As there is no oil to cool down the compression chamber, the temperature increase introduces extra design and production challenges. In order to limit the temperature increase, and also to maintain or improve efficiency, most dry running screw compressors for discharge pressures between 7 to 15 bar(a) are two-stage, with inter- and aftercoolers.

Because of the increased demands put on the design, engineering and manufacturing of dry running screws, only a handful of companies produce them for applications between 7-15 bar pressure.

Water injected screw

Water-injected screw compressors operate very similar to oil-injected screw compressors, other than that the cooling media is water. The water helps to cool the air-end, seals the air trapped in the compression chamber and rotors, and (in some designs) lubricate the bearings. There are also water-injected screw compressors, with bearings and/or synchronisation gears lubricated by oil, separated from the water system by shaft seals.

The design of water-injected screws does introduce design, engineering and manufacturing challenges as the materials need to be extremely corrosion and wear-resistant.

[138] Source: http://www.efficiencyblowers.com/efficiencyblowersus/downloads/technicalwhitepaper/

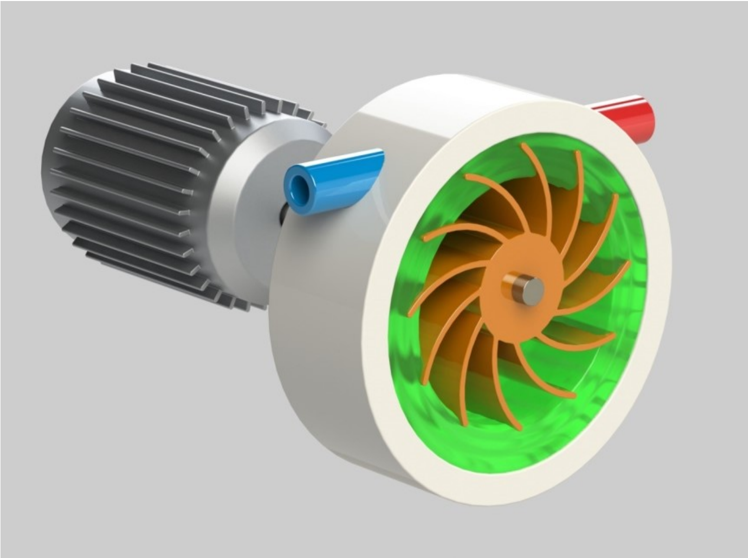
4.3.5 Liquid ring compressors

In liquid ring compressors, the impeller is the only moving part inside the machine. It rotates without contact within the pump casing. A rotating liquid ring seals the impeller on the front and seals its blades against one another. In order to keep the liquid ring stable, liquid is also permanently sucked into the compression chamber and is output together with the conveyed gas [139].

The eccentrically arrangement of the impeller within the casing creates compression chambers between the impeller blades of variable size during rotation, which causes the conveyed gas to be compressed within a full revolution.

The simple construction and presence of the liquid makes these compressors particularly suitable for the harshest conditions, even if solids are sucked in. This design can also provide multiple compression ratios in a single machine in parallel.

Figure 30 Liquid ring compressor – illustration of working principle[140]



The above figure is illustrative only and does not depict a real working machine.

Liquid rings machines are now mostly applied in vacuum systems.

[139] Source: http://www.gd-elmorietschle.com/product.aspx?id=15486&mi=692&smi=732

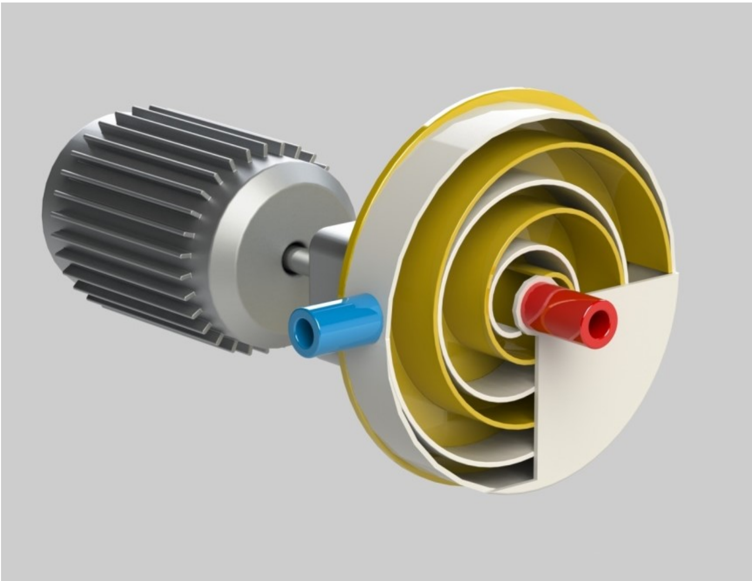
[140] This figure is for the illustration of the basic working principle only, and may contain placing, sizing of components different to 'real' products for the purpose of showing the working principle. It is not intended as a realistic rendering of actual product configurations, as available on the market.

4.3.6 Scroll compressors

Scroll compressors operate in the lower end of the oil-free operating range, competing with pistons mainly.

The benefit of a scroll compressor is it simple design with only one moving part. The air-end has two spiral elements of which one is stationary and the other orbits in eccentric circles. Air is trapped between the two spirals at the suction side and is transported to the centre of the spiral, whilst reducing the volume of the trapped air. Advantages are its quiet operation and low maintenance. Larger scroll compressors may require periodic replacement of the scroll head after 10.000 hours (or 4 years) of operation[141]. Also scroll-compressors are often more expensive than reciprocating compressors of the same capacity.

Figure 31 Scroll compressor – illustration of working principle[142]



The above figure is illustrative only and does not depict a real working machine.

[141] Source: http://www.hitachi-ies.co.jp/english/products/air/scroll/features.htm

[142] This figure is for the illustration of the basic working principle only, and may contain placing, sizing of components different to 'real' products for the purpose of showing the working principle. It is not intended as a realistic rendering of actual product configurations, as available on the market.

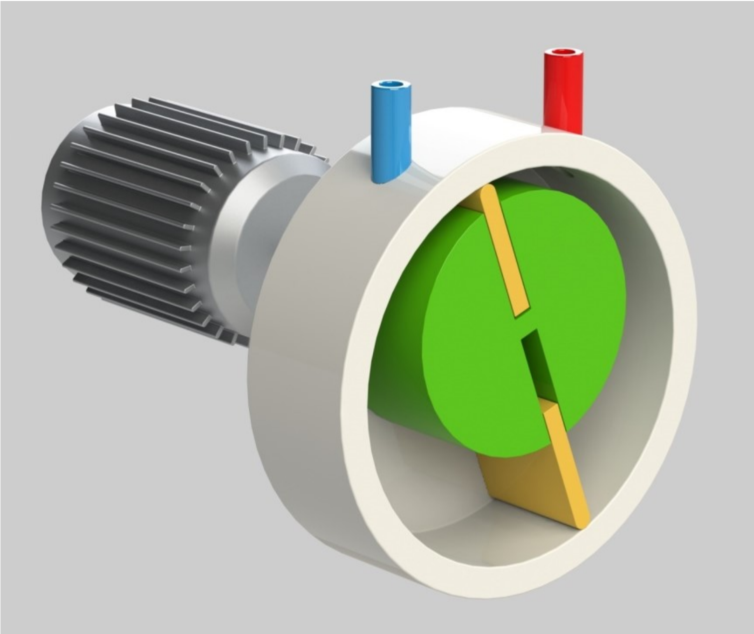
4.3.7 (Dry) Vane compressors

In rotary vane technology, the rotor, the only continually moving part, has a number of slots machined along its length into which sliding vanes fit. The rotor is positioned eccentrically in a cylindrical stator. During rotation, centrifugal force extends the vanes from their slots, forming individual compression cells. Rotation initially increases the cell volume (suction side) and decreases the cell volume afterwards (pressure side), increasing the air pressure.

Rotary vane compressors exist in lubricated (= 'standard air') and dry-running versions. In an oil-lubricated version these vanes ride on a film of oil. In the oil-free version there is no oil in the working chamber.

Vane compressors are compact, fairly robust and require little maintenance. Typical application examples for vane compressors in LP are pneumatic conveying or air supply for print and paper industry.

Figure 32 Dry vane compressor – illustration of working principle[143]



The above figure is illustrative only and does not depict a real working machine.

[143] This figure is for the illustration of the basic working principle only, and may contain placing, sizing of components different to 'real' products for the purpose of showing the working principle. It is not intended as a realistic rendering of actual product configurations, as available on the market.

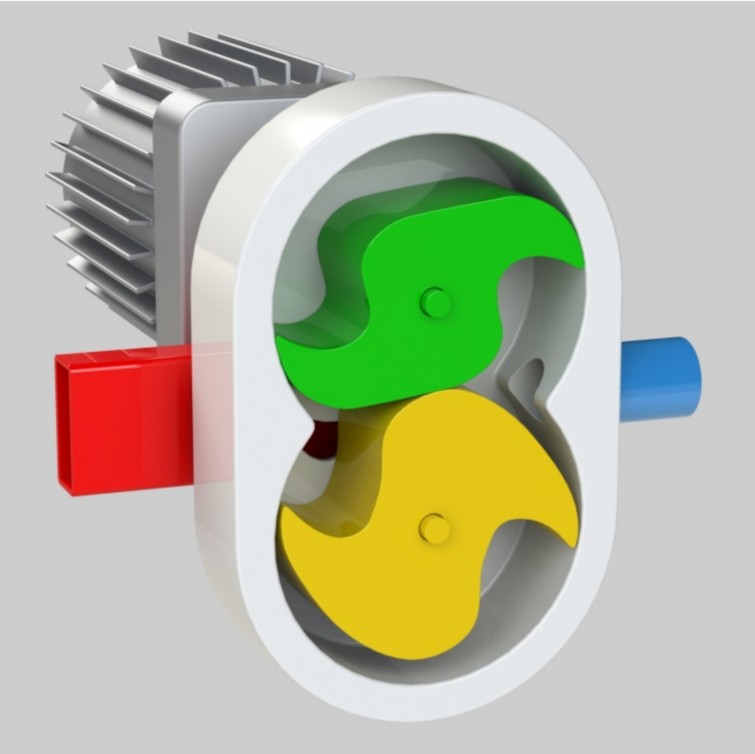
4.3.8 Claw/tooth compressors

The rotary claw technology utilizes two nearly symmetrical, non-contacting contra rotating rotors that sweep the inlet of the compressor creating internal compression without friction or lubrication, creating two discharge strokes per revolution. There is no contact between the rotating parts and no need for lubrication. There is no sealing liquid either, so the air or gas handled is left clean and uncontaminated. There is no wear and no consumption of oil or other liquid. The dry, contactless design eliminates pollution, product contamination, and other environmental issues.

The flow is proportional to the speed and relatively high compression ratios can be used, higher than generally served by lobe or vane technology.

There is a vast variety of shapes of claws, sometimes also referred to as 'tooth' or 'hook'. The basic principle remains the same: Two contra rotating rotors compressing the gas, allowing inlet and discharge through ports.

Figure 33 Claw / tooth compressor – illustration of working principle[144]



The above figure is illustrative only and does not depict a real working machine.

[144] This figure is for the illustration of the basic working principle only, and may contain placing, sizing of components different to 'real' products for the purpose of showing the working principle. It is not intended as a realistic rendering of actual product configurations, as available on the market.

4.4 Turbo compressors

Turbo compressors comprise machines in which inlet, compression and discharge are continuous flow processes. The gas is conveyed and compressed in impellers and decelerated with further increase in pressure in fixed vaned or vaneless stators. They are also referred to as 'dynamic' compressors.

ISO/TR 12942:2011(E) recognises as design classes radial (centrifugal or peripheral), peripheral, axial, diagonal and cross flow (and combinations of these). However, only the centrifugal and peripheral flow compressors are relevant for the low pressure and oil-free application range.

4.4.1 Centrifugal turbo compressors

Centrifugal compressors draw in air at their centre by a rotating impeller and accelerate this air, increasing air velocity. The air then passes a narrow opening before entering the diffuser area, at the periphery, which restricts the flow in a predetermined manner (more specifically: depending on impeller type and individual impeller design a relevant fraction of static pressure increase by deceleration of flow speed may take place in the impeller wheel itself). As the air velocity slows down, the pressure (and temperature) rises.

A basic single-stage centrifugal turbo compressor has few moving parts, resulting in relatively low maintenance requirements, but multi-stage integrally geared turbo compressors with variable inlet and diffuser guide vanes can be quite complex.

As internal clearances are relatively high (tenths of millimetres) and for difficulties in managing the efficiency, the pressure ratio per stage is limited to maximum 3.5. Single stage centrifugal turbo compressors are generally used for applications requiring high volumes at low pressure ratios – such as in aeration / oxygenation, furnaces, low pressure cooling, dust or fume extraction systems, lean phase pneumatic conveying etc.[145].

Multi-stage compressors, running at high speeds, can achieve pressures of 13 bar(e) and are applied in the 'oil-free' application range.

Oil may be used for lubrication of gears and bearings, but these components are always shielded from the pressure side by proper seal-arrangements. The air is oil-free.

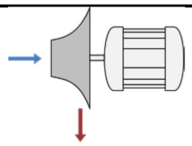
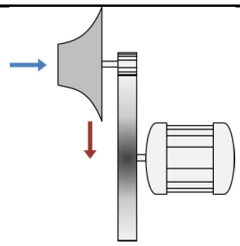
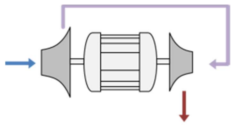
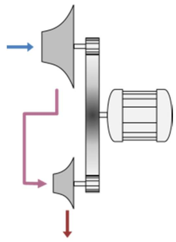
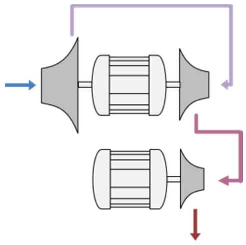
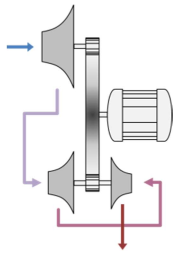
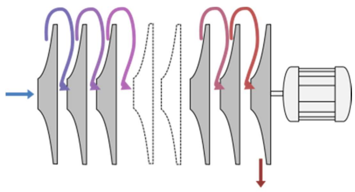
Overall energy efficiency is relatively high, but influenced by changing operating conditions. In dynamic compression the inlet temperature and mass flow (density) have a direct effect on the power of dynamic compressors. The density of the gas will influence how much power is required to compress to a certain mass of gas to a certain discharge pressure.

[145]http://www.process-worldwide.com/understanding-blowers-how-to-make-the-best-use-of-blowers-and-compressors-a-373637/

Categorisation by stages and driving arrangement

Turbo compressors can be differentiated by their number of stages, whether the rotor is driven directly by the electric motor, the drive arrangement (gear) applied.

Table 58 Turbo compressors by number of stages and driving arrangement

	Direct drive	Integrally geared	In-line
Single stage			[n.a.]
Two-stage			[n.a.]
Three-stage			
Multi-stage[146]	[etc.]	[etc.]	
Volume flow range	min 1000 m^3/h max 20 000 m^3/h	min 1000 m^3/h max 100 000 m^3/h	min 8000 m^3/h max 50 000 m^3/h

[146] The "in line" multistage centrifugal is rarely called a turbo.

Direct drive

In direct driven centrifugal compressors the rotor is directly driven by the shaft connected to the electric motor shaft.

Figure 34 Single stage / direct drive centrifugal compressor – illustration of working principle

The above figure is illustrative only and does not depict a real working machine.

Multi-stage compressors can be realised by connecting a second rotor to the other end of the motor shaft (2-stage) and or by adding another rotor/motor combination in the package (3-stage, etc.).

The rotating speed of a rotor of a centrifugal compressor is an inverse function of its diameter to maintain a desired peripheral speed at the outer diameter of the impeller regardless of the physical size of the compressor (i.e. to achieve the optimum specific speed). Therefore smaller compressors operate at speeds much higher than the standard 2-pole, 50 Hz motor at 3000 rpm, and run between 15.000 to 50.000 rpm.

For better performance smaller impellers need to be run at higher speeds than that of a standard 2-pole induction motors[147]. This can be achieved by belt ratios (uncommon), gears (design referred to as 'integrally geared') or by application of high speed motors (for instance a synchronous permanent magnet motor equipped with a variable speed drive).

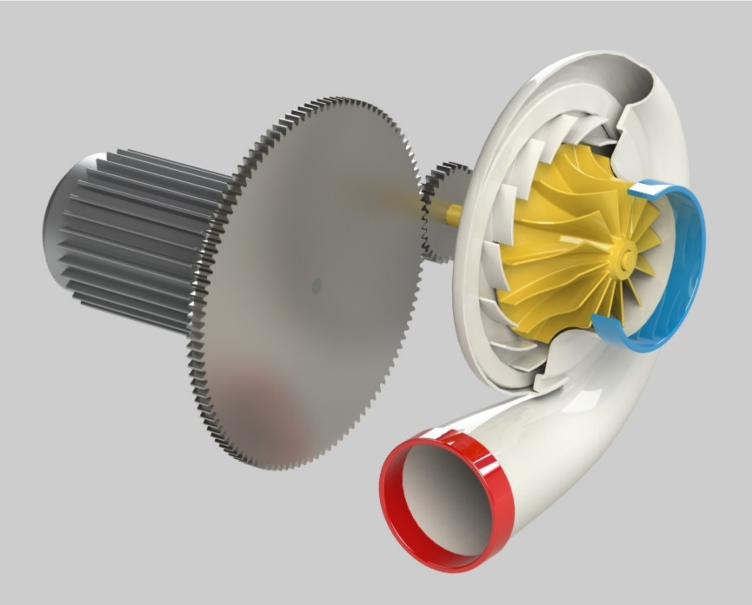
Integrally geared

In an integrally geared centrifugal turbo compressor, the rotor(s) are driven by pinion gears that are driven by a main (bull wheel) gear. The gear ratio allows for sufficient high rotational speed of the rotor, whilst being driven by conventional speed motors.

The gear ratio between the pinion gear and the bull gear is about maximum 1/20, so that 3000 rpm is increased to 60000 rpm.

[147] Note: this design can also be applied in two- or more stage set-ups, but the 'single stage' is the most common high speed turbo compressor.

Figure 35 Single stage / integrally geared centrifugal compressor – illustration of working principle



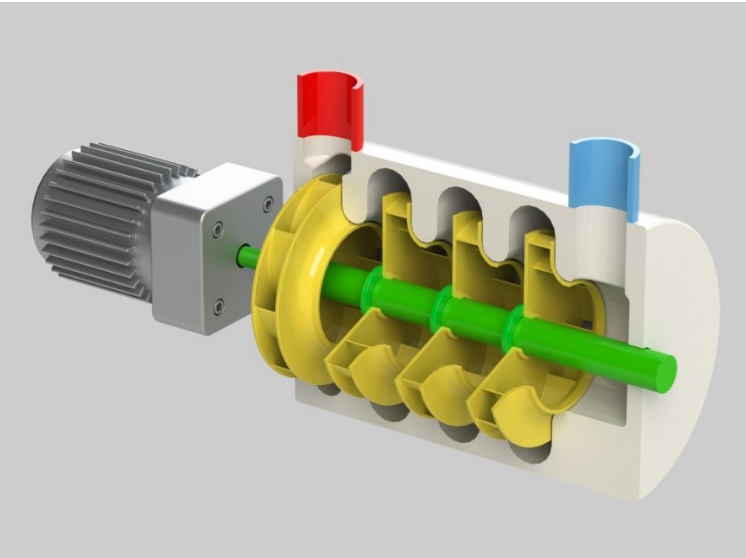
The above figure is illustrative only and does not depict a real working machine.

Multi-stage compressors have multiple rotors driven by the central bull wheel. The planetary gears allow optimising the speed of each rotor.

In-line (multi-stage only)

The multistage/in-line centrifugal compressor consists of a single axis that carries multiple impellers. The outlet of the first impeller is connected to the inlet of the subsequent impeller(s) thus generating multiple stages.

Figure 36 Multi-stage / inline centrifugal compressor – illustration of working principle



The above figure is illustrative only and does not depict a real working machine.

There is a variety in impeller numbers and arrangements, depending on the pressure/flow required. When intercooling is not needed, the arrangement is usually a straight-through (inline) configuration.

For applications that require intercooling, the resulting two-section compressor may be configured in either an inline (compound) or back-to-back arrangement.

For high-flow/low-head applications, a double-flow configuration is sometimes employed. In a double-flow arrangement, half of the flow enters the compressor through an inlet connection at each end of the casing and exits the casing through a common discharge connection in the centre. All of these configurations described are beam-type designs in which the impellers are located between the radial bearings[148].

The design involves some extra losses due to the redirection of the tangential air flow towards the axial inlet of the subsequent impeller. As the impellers rotate with the same speed the geometry of the housing (diffuser area, inlet path) is changed to account for the pressure ratio over the single impeller (inlet and outlet conditions).

Multistage/in-line centrifugal compressors operate at much lower speeds than single-or two/three stage compressors, typically some 3000 rpm (3600 rpm in USA, at 60 Hz).

Bearings for high speed turbo compressors

As the shafts of high speed turbo compressors rotate at 15,000 to 50,000 rpm two bearing technologies for specifically such high rpm are applied, besides conventional roller and oil journal bearings:

1. air foil bearings and
2. magnetically levitated bearings.

Air foil and magnetic bearings have differences in features and price points, but both can be applied cost effectively in machines. The simplest comparison is shown in the table below.

Table 59 Simple comparison of oil journal, air foil and magnetic bearings[149]

Bearing aspect	oil journal	air (foil) bearing	magnetic bearing
Working medium	oil	air	electric current
Shaft supported by	oil film	air pressure	magnetic field
Medium delivered by	oil pipes or sump	ambient air source	MBC algorithms
Bearing stability control	passive	passive	active
Key support component	oil pump	shaft speed	controller amplified
Support component back-up	none	none	backup rolling elements bearings and UPS battery backup
Bearing health monitoring	passive temperature and vibration sensor	passive temperature and vibration sensor	active position sensors, multiple temperature sensors, remote monitoring

[148] http://petrowiki.org/Centrifugal_compressor

[149] http://www.airbestpractices.com/industries/wastewater/high-speed-bearing-technologies-wastewater-treatment-applications

Contacting	at start up and low speed	at start up and low speed	never (unless failure)
Inherent monitoring	none	none	temperature, vibration, proximity to surge, system stability
Cost (of bearing only)	low, but cannot be applied in all applications	low (bearing only – does not apply to complete machine)	high

Magnetic bearing control requires extensive control loops with the bearing controller. The position of the rotating assembly may be monitored at 10,000 times per second using position sensors incorporated into the bearing. The sensors pass the information to the controller, which performs calculations and adjusts power sent to the electromagnets of the bearing. This also offers the ability to dynamically adjust bearing characteristics and this allows for a wide stability range, self-protective algorithms, and collection of data for health trending purposes. Shaft position can be related to vibration, dynamic imbalances, and internal diagnostics of the bearing. Temperature sensors detect overall condition of the bearing and the control circuitry.

Additionally, the above data can be used to analyse system resonances, gyroscopic effects, and overall system stability. If a problem is detected, the machine will automatically shut down to protect itself from damage. The collected data can be analysed further to monitor trends, and make comparisons to other machines, etc.

With **air foil bearings** health monitoring is possible using passive temperature monitoring, but the response time is an issue. Using appropriate vibration sensors, imbalances and shaft position can be monitored.

Performance maps

Centrifugal turbo compressors are mass-flow devices which means the power requirement for a rated volume flow at rated pressure is determined by the weight (mass) of the air. The performance of a turbo compressor (simple ones, with no volume flow control) thus varies with changes in operating conditions such as inlet pressure, inlet temperature, cooling water temperature (if applicable) and discharge pressure.

Generally speaking, increasing the inlet temperature reduces the density of air, thus reducing the mass flow, the volume flow, and input power requirement. Increasing cooling water temperatures ('hotter' water) between stages or a reduction of the inlet pressure (as occurs at higher altitudes, or negative compressor room pressure, but also by dirty or poorly sized inlet filters) has a similar effect as increased inlet temperature, reducing flow and power.

Figure 37 Effect of inlet air temperature on volume flow or pressure[150]

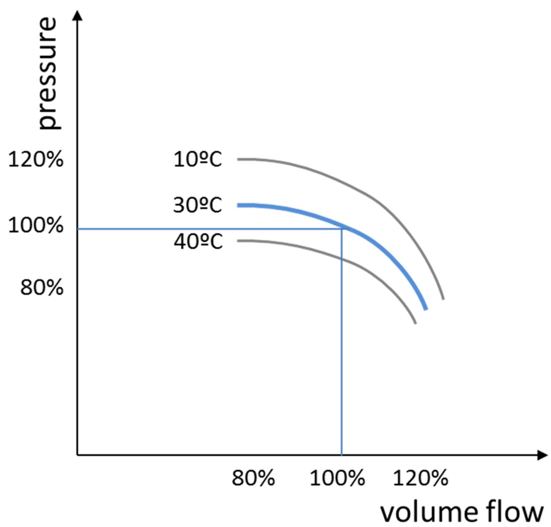
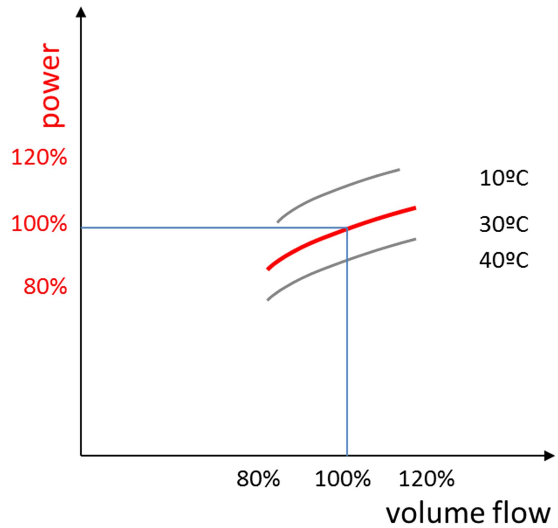


Figure 38 Effect of inlet air temperature on power



Colder inlet temperatures, higher inlet pressure or colder cooling water will have the opposite effect, increasing mass flow, volume flow and power requirement.

Increasing the discharge pressure increases the mass flow through the stages and results in less volume flow at same input power. Lowering the pressure will allow more flow at similar power input.

The actual net effect of any of these conditions is dependent of the actual performance curve and aerodynamic characteristics of the design.

The isentropic head (abstract and simplified) of turbomachinery is calculated using:

Equation 12 Isentropic head

$$H = R * T_1 * \frac{k}{k-1} * \left\{ \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1 \right\}$$

Where:

H: Isentropic head [W]
R: Real gas constant [-]
T1: Inlet temperature [K]
κ: Specific heat ratio c_p/c_v [-]
p_2/p_1: Pressure ratio [Pa]

Isentropic head (or more precise "isentropic enthalpy increase") is not specific to turbo compressors. "Mass flow rate" times "isentropic enthalpy increase" gives "isentropic power requirement". This parameter is needed for the calculation of "isentropic efficiency" for every type of compressor.

The figure below shows typical performance map of a (centrifugal) turbo compressor. The red lines are constant speed curves, showing how flow and pressure are linked at given speeds. On the left side the speed curves are cut-off by the surge limit. On the right the speed curves are cut-off by the stonewall or choke limit. The general slope of the constant speed curves changes with the number of stages, becoming steeper with an increasing number of stages.

[150] This is only an indicative example. Different curves exist for specific equipment.

The design point should be selected so that a safe margin from surge and choke exists, and close to optimum efficiency. Typically the best efficiency point is located somewhere on a constant speed curve and, with changing speed, travels up and down a system curve.

Figure 39 Typical performance chart (pressure / volume flow) of a centrifugal compressor, with variable speed, and lines of constant efficiency drawn

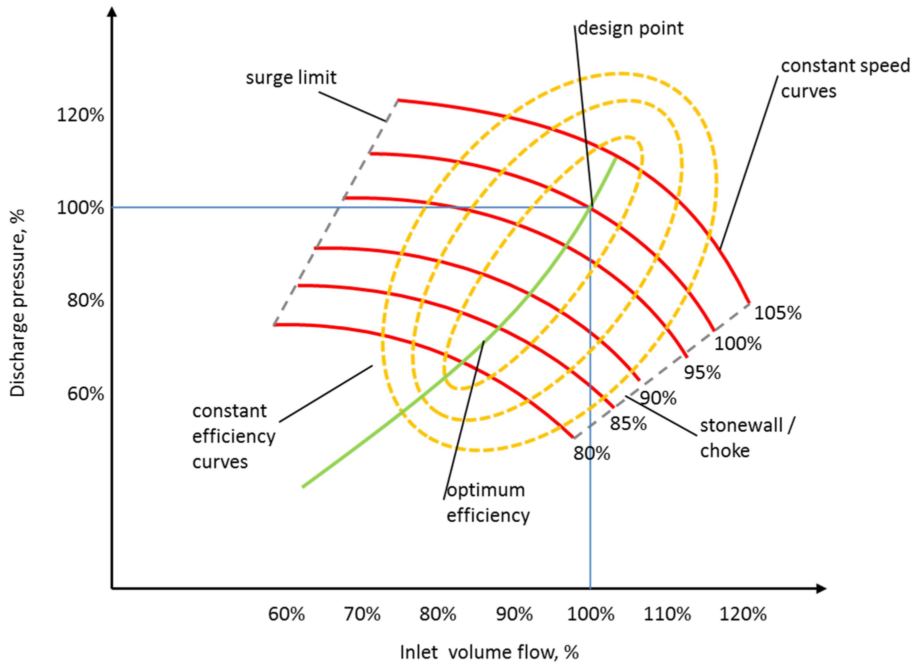
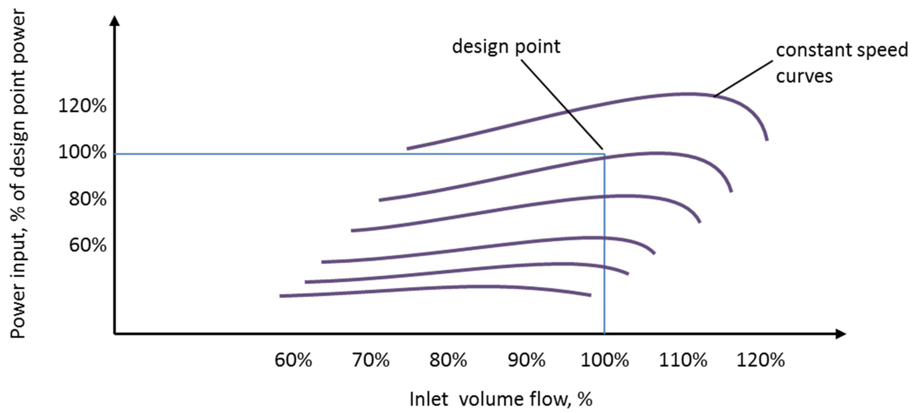


Figure 40 Typical performance chart (power vs volume flow) of a centrifugal compressor, with variable speed



The power curve exhibits a minimum defined by the surge conditions, followed by a steady increase at larger flows, and a sudden drop when the compressors hits the choke point.

Surge, choke, turndown (flow control range) are elaborated upon below.

Surge

The surge point on a single speed curve is where the volume flow becomes aerodynamically unstable. It indicates the minimum of the volume flow control range (lower volume flow rates at given speed, given pressure, cannot be reached).

Surge occurs when a combination of lack of airflow, consequent rise in pressure, and high speed of the compressor all cause the compressor blades to effectively lose their “grip” on the air. Aerodynamically speaking, the air separates from the back of the compressor blades, allowing some air to escape back out through the compressor. The resulting pressure drop in the intercooler piping (downstream) allows the blades to “grip” again which, under the residual momentum of the turbo, will increase the pressure and the cycle repeats. This causes the characteristic fluttering sound of compressor surge, and also results in pressure pulses in the intercooler piping.

When operating in a surge condition, the compressor discharge temperature increases significantly and the compressor experiences erratic and severe vibration levels that can cause mechanical damage—particularly to the internal seals. Most centrifugal compressors are equipped with vibration monitors and will shut down to avoid this condition.

A compressor can be brought out of surge by either increasing speed, decreasing discharge pressure and/or increasing the flow by application of anti-surge valves.

Anti-surge valves are located in a line connecting the compressor discharge to the inlet. Instrumentation measures flow, and a surge controller initiates the opening of the anti-surge valve when the flow approaches the surge limit. The flow at which the anti-surge valve begins to open is usually set to be about 10% larger than the actual surge limit. The gas travelling through the anti-surge valve must be cooled because its source is the compressor discharge.

Choke (*"stonewall"*)

The choke limit of the performance curve defines the maximum flow at which the gas velocity of the impeller(s) approaches the speed of sound and discharge pressure falls at any greater flow.

The power curve shows a sudden drop as the falling discharge pressure results in reduced mass flow, reducing the input power. Continued operation at or beyond this point can cause cavitation-like action, creating another type of surge with damaging vibrations. Most centrifugal compressors are equipped with vibration monitors and will shut down to avoid this condition.

Flow control range

Centrifugal compressors need to be designed to produce the rated flow and pressure also on the hottest day expected at their installation location (the highest intake air temperature results in the lowest flow at the same pressure, as centrifugal compressors are mass flow devices). This means that at lower temperatures than maximum the compressor delivers more air than required (if multiple units are use, one can turn off some). Since this additional air is normally not required, the compressor intake of a single speed design must be throttled to match the plant demand.

There are various methods to vary the flow while maintaining a constant discharge pressure.

Speed control

By increasing the speed of rotation the volume flow is increased for a given discharge pressure. Conversely, capacity may be decreased by reducing compressor speed. Capacity control by speed variation is the most effective way to maximize the operating flexibility of a centrifugal compressor.

Depending on discharge pressure, the minimum volume flow rate is typically 70% to 60% of the maximum volume flow rate for higher pressure applications or 50% to 20% for low pressure applications.

The application of variable speed drives does come at a cost and reduces the efficiency when driven at a single speed only compared to fixed speed designs.

If the compressor has a fixed-speed motor, it is usually dimensioned for the operating condition that requires the largest volume flow for the required discharge pressure. If a single speed compressor reduces its volume flow, the pressure would increase.

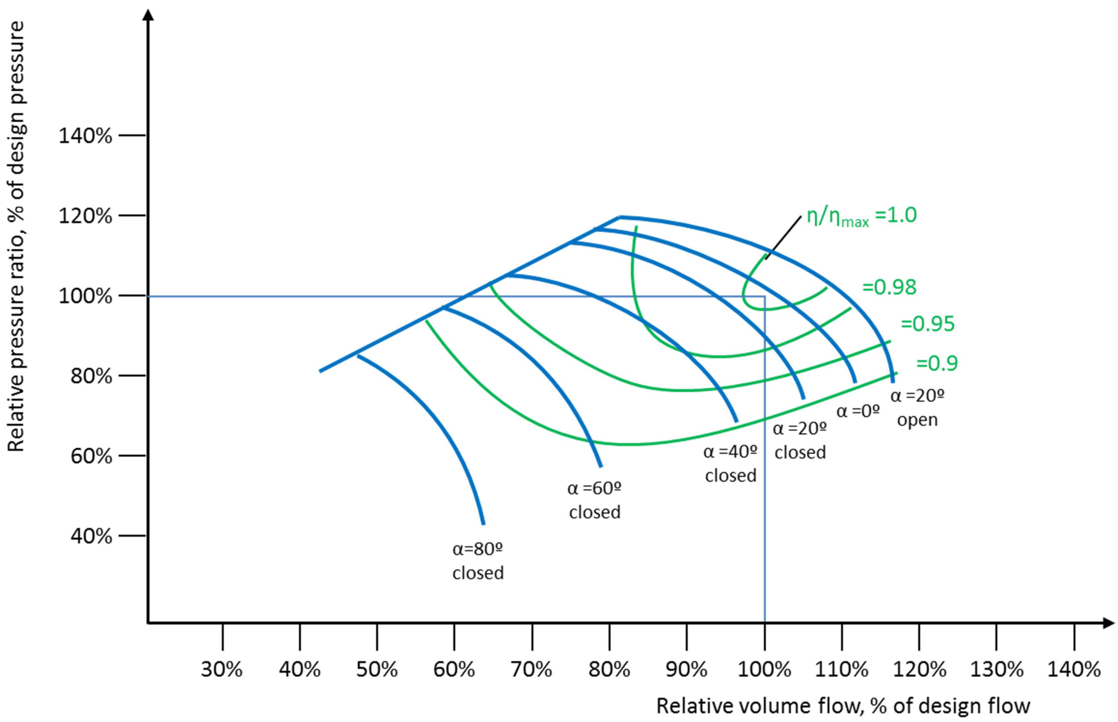
A throttle valve (like a butterfly valve) can reduce discharge pressures, to even out a pressure increase at lower volume flow. Suction pressure reduction by throttling increases the pressure ratio required to deliver a given discharge pressure. The efficiency of the compressor will drop as a result. The economic trade-off for this method of capacity control is additional compressor power vs. additional capital expenditure for a variable speed drive.

Compared to variable inlet guide vanes, the throttle valves requires some 8-9% more power near full closure, reducing efficiency by the same amount.

Variable inlet guide vanes

Variable inlet guide vanes adjust the direction of air flowing into the compressor ('pre-rotation of flow"). By changing the angle of the vanes, it is possible to maintain a desired discharge pressure over of a volume flow range. Due to this pre-rotation, less power is required to compress the incoming airstream.

Figure 41 Inlet guide vanes control



For single stage compressors, this method of control can be quite effective. For multistage compressors, inlet guide vanes are less effective with increasing numbers of stages, as the inlet guide vanes angle can only be optimised for a single stage.

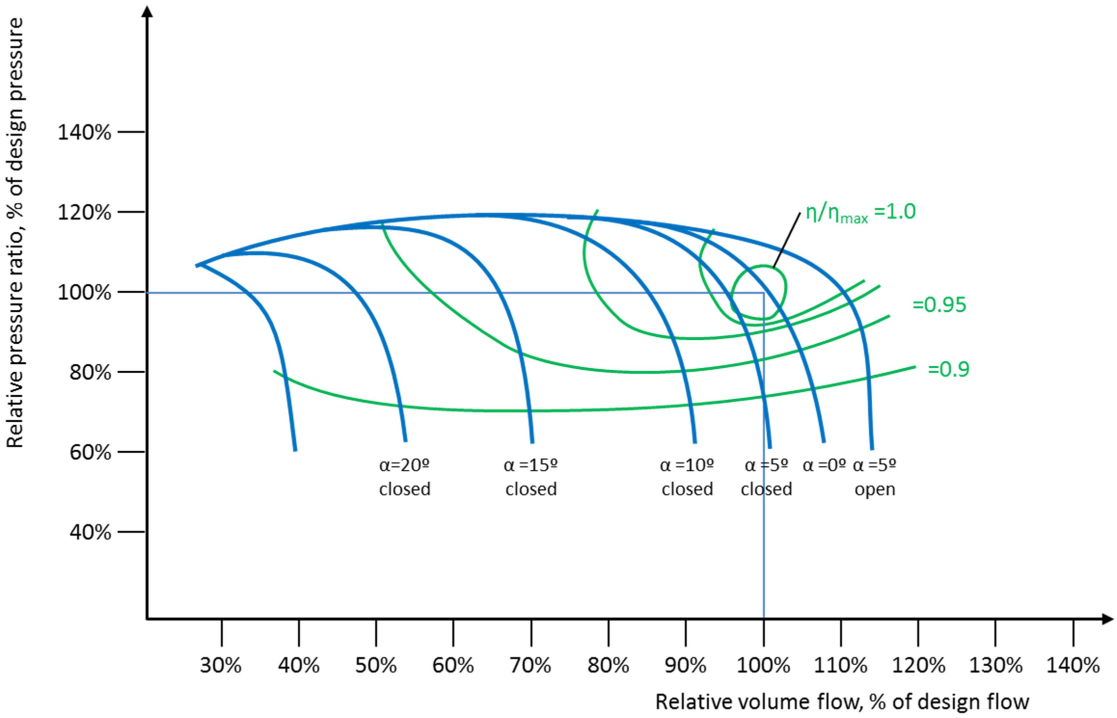
Installing variable vanes at other stages introduces practical design limitations.

Variable diffuser guide vanes

The diffuser guide vanes are located at the stator, close to the periphery of the rotor. In this area the air leaves the impeller at high speeds, just before entering the diffusor area. By directing the air as it leaves the impeller, before entering the diffusor area, the air flow through the machine can be controlled and the machine can be made to operate at part load conditions.

Diffuser guide vanes and inlet guide vanes can be combined in a single machine.

Figure 42 Diffuser guide vanes control



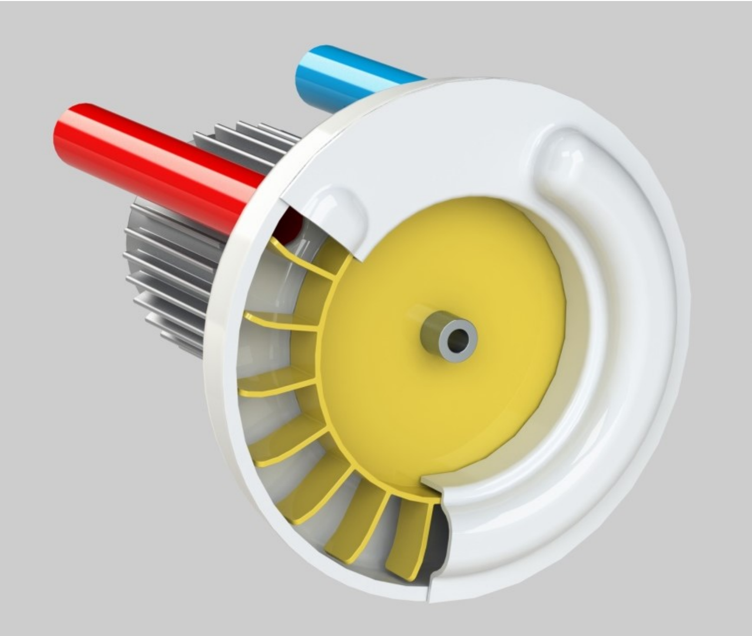
4.4.2 Regenerative or side-channel compressor

Regenerative or side channel compressors are also called "vortex", "peripheral" or "ring" compressors. Most are direct driven but belt drives can be used.

The rotor rotates in a stator (housing) with a channel close to the peripheral blades (hence side channel blower). As the blades pass the inlet port, they draw air in, which is then pushed outward and forward into the channels. The air then returns to the base of the blade to be pushed by the next blade into the side channel. The process repeats continuously until the air reaches the discharge port.

A regenerative blower essentially operates as a multistage compressor. Each blade-to-blade regeneration stage results in a slight pressure increase.

Figure 43 Illustration of working principle of regenerative or side channel blower



The above figure is illustrative only and does not depict a real working machine.

Note: to make the inlet and outlet ports better visible these have been drawn on the top side of the machine, normally they are on the bottom side of the machine.

The performance of regenerative blowers very much depends on the number, size, and angle of the blades on the rotor as well as the design of the stator (housing). Regenerative blowers can be designed to have a rather flat performance curves or rather steep curves. They are suited for both pressure as well as vacuum applications.

Typical regenerative blower applications include sewage aeration, vacuum lifting, vacuum packaging, pneumatic conveying, concrete aeration, pond aeration, vacuum tables, drying, dust/smoke removal, air sparging, and chip removal[151].

In a one-stage unit, the path between inlet and discharge is roughly the circumference of the housing. Two-stage regenerative blowers can provide almost twice the pressure or vacuum of single-stage units. Instead of being discharged, the air is channelled to the backside of the impeller through internal porting. Air then makes another revolution around the backside of the same impeller before it is discharged. Other two-stage configurations are also available, including designs that use two separate impellers in one housing or two impellers and housings.

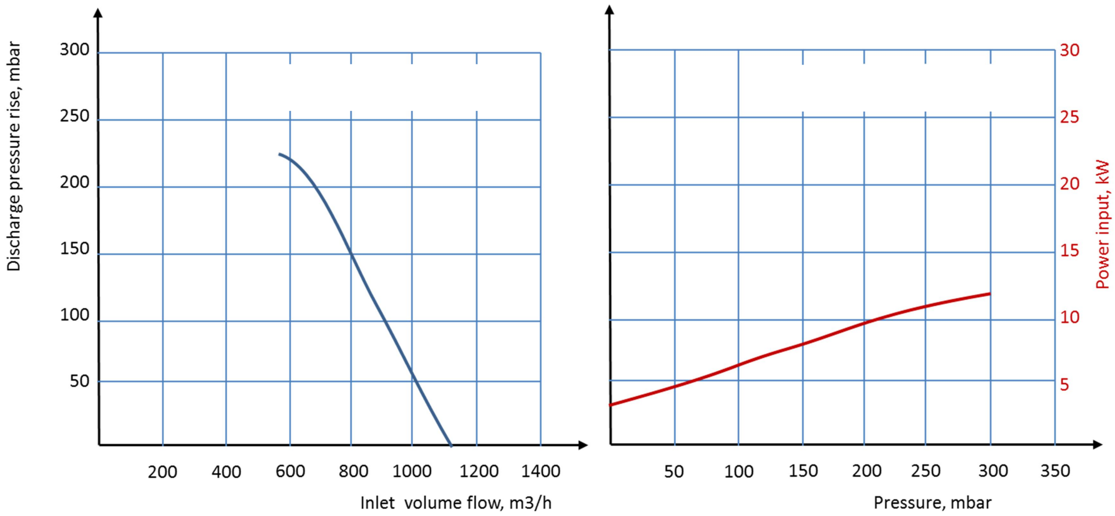
[151] http://www.controleng.com/single-article/regenerative-blowers-move-low-pressure-air-effectively/1cf52524ea7fc11ba989b667285e4b76.html

Single-stage (one-stage) side channel blower operate typically in a pressure range between 0 – 300 mbar with a typical max. volume flow of 70 l/s (250 m^3/h).

Multi-stage (two- or three-stage) side channel blowers operate typically in a pressure range between 0 – 700 mbar with a typical max. volume flow of 100 l/s (360 m^3/h).

Typical performance curves of regenerative blowers are relatively steep, when compared to other centrifugal blowers or even fans, but not as steep as positive displacement blowers.

Figure 44 Performance curves flow-pressure and pressure-power of a side channel blower



Benefits vs drawbacks

Among the major benefits of a regenerative blower is that it requires little maintenance and has few monitoring requirements. The impeller is the only moving part and is wear free and does not come in contact with the housing channels. Self-lubricated bearings are the only parts that wear.

Although the energy efficiency of regenerative blowers is generally lower than that of equipment supplying a similar pressure/volume flow, the combination of certain characteristics still make them an attractive option.

Below is a list of characteristics of side-channel blowers :

- Volume flow range: 40 – 1500 m^3/h;
- Pressure range: 0 – 0,5 bar(g);
- Completely oil free (no gearbox, no oil lubricated bearings);
- Low efforts for installation and maintenance;
  - Wear-free (except bearings);
- Small frame dimensions and low weight (easy integration in OEM machine, precious space in OEM machine is saved);
- Low noise emission, very little vibration (no need for sound proof box);
- No pulsation (ideally suited for pulsation sensitive applications);
- Continuous operation at low differential pressure possible (only few monitoring requirements);
- Stable characteristic curve;
- Wide volume flow range with VFD (e.g. rotor speed 10% - 100%);

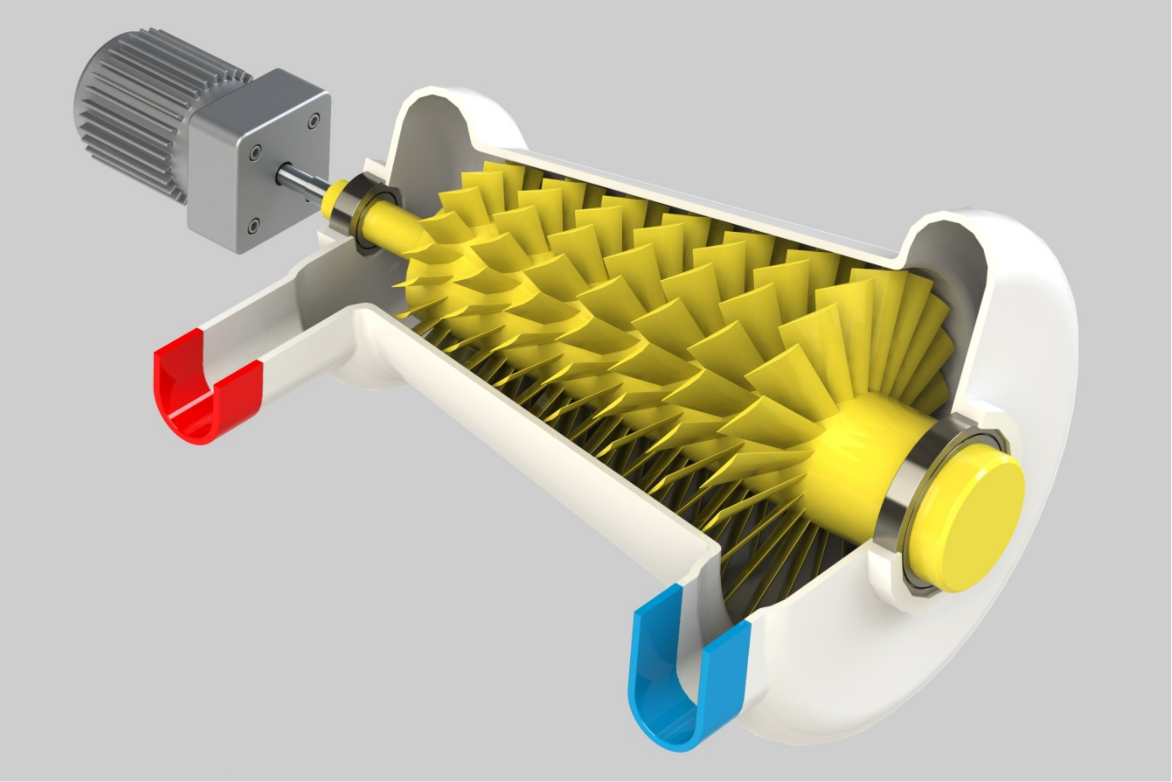
- Low material consumption in production (resource-efficient, eco-sensitive);
- Robust against environmental influences;
- Small volume flow/pressure units available.

The combination of these characteristics allows side channel blowers to be used in many different applications: Especially the combination of small frame dimensions and low weight, continuous operation at low differential pressures and low efforts for installation and maintenance are difficult to match by other technologies .

4.4.3 Axial flow compressor

Contrary to centrifugal machines the air flow of an axial type is parallel to the axis of rotation. The pressure ratio per stage is rather limited, indicatively between 1.05 – 1.2, but happens at high efficiency (88% to 92%) and as multiple stages are applied the overall pressure ratio can be considerable.

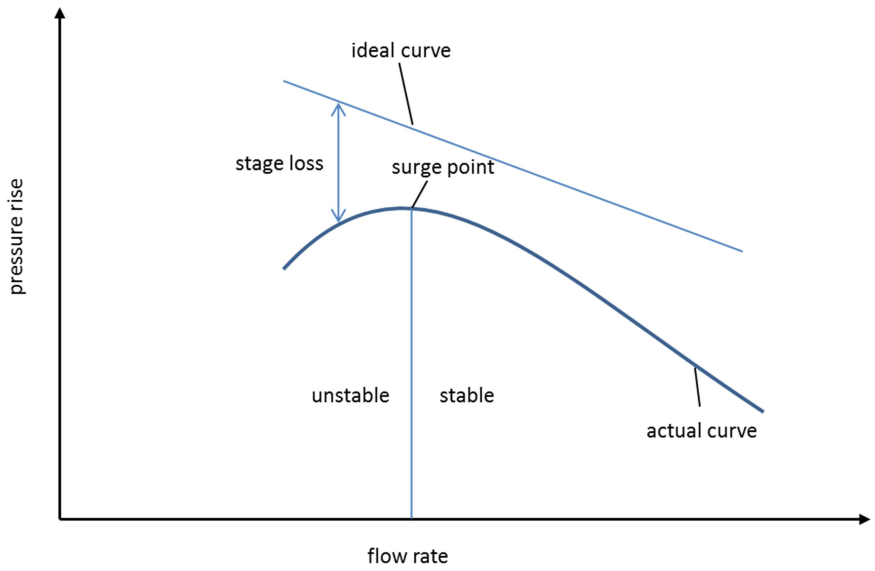
Figure 45 Illustration of working principle of axial flow compressor



The above figure is illustrative only and does not depict a real working machine.

Similar to centrifugal turbo compressors, there is a surge point beyond which performance becomes unstable.

Figure 46 Typical performance curve axial flow turbo compressor



The maximum volume flow to be achieved is larger than any other type of compressor described in this Task and can reach up to 1,5 million m³/h. The maximum discharge pressure to be achieved is up to 25 bar.

The main application areas are high volume flow industrial applications such as:

- blast furnace blowers;
- air separation plants;
- fluid catalytic cracking;
- nitric acid plants;
- liquid natural gas;
- wind tunnels;
- propane dehydrogenation;
- fuel gas (low BTU);
- CO_2;
- CAES (compressed air energy storage – in underground cavities etc.).

Examples of major axial compressor manufacturers are MAN, Siemens, Dresser-Rand, General Electric, and Elliot Group.

Hybrid designs, combining axial and radial (centrifugal) designs, are also developed, such as the MAN AR range.

As axial compressors are not commonly used in the low pressure or 'oil-free' (between 7 to 15 bar(a)) application range **they will not be considered any further**.

4.4.4 Other dynamic compressors

In addition to the above types, the compressor literature also describes "mixed flow compressors" which are characterised by an air flow path with an angle in-between that of centrifugal and axial compressors. The performance is therefore also typically between these two designs.

And the "cross-flow" compressor whose design is described in ISO/TR 12942 but is rarely applied in applications relevant to this study.

As mixed- and cross-flow compressors are rarely used in the low pressure or oil-free' application range **they will not be considered any further**.

4.5 Part load operation[152]

As stated in Task 3, most compressor applications require operating in variable pressure and/or volume flow conditions, which means there is part load behaviour. The behaviour of a compressor at part load depends on both the compressor technology (type) and flow control technology. It should be understood that not all flow control technologies are applicable for all compressor technologies.

The following flow control methods apply to fixed speed packages.

Start/stop

This is a very simple control option, typically applied for positive displacement equipment only, in the low power range (max 20 kW indicatively).

With start/stop a pressure switch provides the motor start/stop signal. It should be applied in systems with sufficient capacity of air receivers as frequent start/stops could overheat the electric motor.

Benefits are that during stop, the energy consumption is virtually zero. Drawback is that, for the system to supply sufficient flow when the compressor is off, it will work against a higher receiver pressure.

Dual control in small reciprocating compressors means a selectable control mode for either start-stop or load/unload.

Load/unload

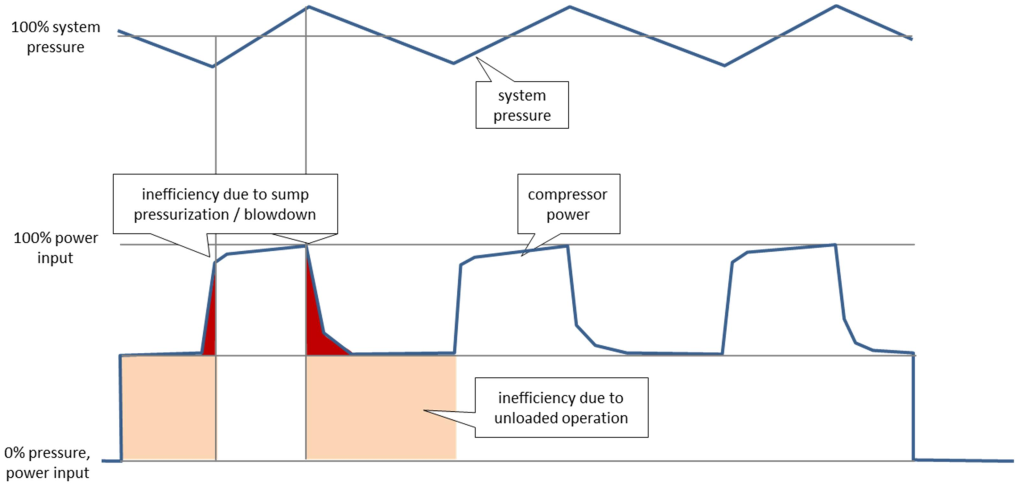
This type of control is typical for oil-free applications, but not so typical for low pressure (up to 2 barg). Load/unload control allows the motor to keep running however in unloaded (blow off) conditions. When a compressor unloads usually the inlet valve closes and the discharge pressure is vented to atmosphere. During unload only small amounts of air, at low pressure ratio, are compressed and power consumption is reduced. Unloaded the compressor typically consumes some 15-35% of their full load power.

As unloading involves releasing pressurised air and loading involves pressurising the equipment, there is energy loss during these transient conditions. While these transitions are taking place, the compressor is consuming power over and above what it takes to produce the compressed air the system actually requires[153].

[152] The section is based on information from the Compressed Air Challenge "Sourcebook for industry" and Atlas Copco's "Compressed air manual – 7th edition".

[153] http://www.plantservices.com/articles/2010/08aircompressorefficiency/

Figure 47 Cycle losses [154]



The higher the capacity of the receiver(s) the lower the power demand can be.

In case of lengthy (> 15 minutes) unload conditions it is probably better to turn the compressor off.

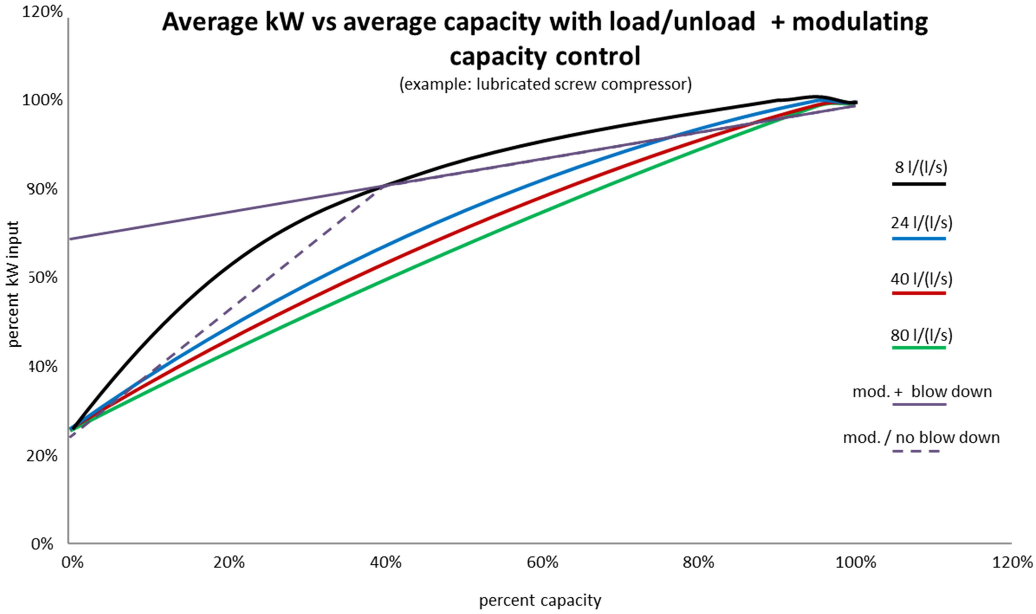
In the case of load/unload, the opening and closing of a valve fitted to the intake of the compression control element controls the compressor's output. The valve has only two operating positions: fully open or fully closed. When the valve is open, the compressor delivers full output. When closed, it delivers zero output. To produce 70% of flow, the compressor operates loaded (100% of flow) at 70% of the time and unloaded 30% of the time. The drawback is that when the compressor is unloaded, the main motor and cooling fan are still rotating and consuming 20% to 40% of full power. Eliminating unloaded operation can save energy[155].This loading and unloading is controlled by upper and lower pressure set points monitored by a pressure transducer or triggered by a pressure switch. The compressor unloads at the upper setting and loads at the lower setting. This built-in operating differential means the air is over pressurized, which consumes additional energy.

An additional drawback with conventional compressors driven by a fixed-speed ac induction motor is that the motor itself limits compressor operation. Unloading the compressor starts a timer. Provided there is no demand for air, the motor stops only when the timer has cycled. The timer usually is set for a 10-minute run-on time, which allows the motor to cool and puts a physical limit on the number of motor starts per hour. So for a 10-minute run-on, only six starts per hour are permitted, and for each 10-minute run-on period, the motor is consuming 20% to 40% of full power.

[154] http://www.nrcan.gc.ca/energy/products/reference/14970

[155] http://www.plantservices.com/articles/2003/415/

Figure 48 Average power by capacity for load/unload and modulating control[156]



Modulation or throttling of centrifugal compressors

Modulating control means throttling the inlet (modulation of discharge is also possible) to meet flow requirements. Flow is controlled by adjusting an inlet valve(s), restricting the air aspirated by the compressor. The method is less efficient than load/unload, as the compressor typically still consumes some 70% of full load power at minimum (zero) flow. This method is applied to centrifugal compressors and lubricant-injected screw compressors. It is typically not applied to reciprocating or oil-free rotary screw compressors, so its relevance in this report is mainly limited to centrifugal compressors only (if applied to oil-free rotary equipment it would increase the pressure ratio, leading to higher air temperatures that could ultimately damage the machine).

For centrifugal compressors modulation can also be achieved by using inlet guide vanes, which is more energy efficient than simple throttling. Inlet valve modulation typically allows the flow to be reduced to some 40% of full flow and can be combined with diffuser guide vanes as well.

Equipment may combine modulating control with load/unload control whereby the equipment is unloaded if the discharge pressure at full modulation reaches full load pressure plus the pressure differential for load/unload.

Variable displacement

Single speed reciprocating compressors can achieve lower flow rates by partially unloading stages. Often the controls are dual-control (see above) or allow regulating flow in 3 (0%, 50% and 100%) or 5 steps (0%, 25%, 50%, 75% and 100%). Typically there is an almost direct relation to motor input power and loaded capacity.

Variable speed

Compressors with variable speed drives (or VFD – variable frequency drives) allow control over the speed of the drive motor. Typically this control method is more energy efficient than

[156] This figure is a combination of figure 3 and 4 of: http://www.airbestpractices.com/system-assessments/compressor-controls/optimizing-specific-power-part-loaded-compressed-air-systems and combined with http://fluidpowerjournal.com/2015/04/choosing-air-compressor/ . The l/(l/s) refers to the air storage capacity of the system.

controlling the flow of a fixed speed machine using start/stop, load/unload (or, if centrifugal, modulating control).

In a positive displacement machine, the volume flow is directly proportional to motor speed. As the efficiency of the positive displacement machines is somewhat lower outside the optimum range (unlike other dynamic equipment like centrifugal compressors or most pumps, fans) the torque requirement is somewhat higher at lower speeds.

Reduced speed reduces the power consumption of the package. There is however a difference between how a positive displacement machine is affected and how dynamic machines are affected.

In positive displacement machines, the power consumption reduces proportional to the speed.

In dynamic machines, the 'Fan Laws' apply. This means (in simple terms) that:

1. the flow changes proportionally to the change in speed;
2. the pressure (or head) changes by the quadratic change of the speed;
3. the power consumption changes by the cube of the change in speed.

This would imply that, as an example, a 50% speed reduction would reduce power to one-eighth of the former power consumption (0.5^3 = 0.125). This relation does not apply to dynamic compressors however, as the back pressure will force the machine to a new working point. Performance data shows that power consumption is approximately proportional to change in speed.

Table 60 Overview of flow control methods

Generic form of control	Positive displacement (oil-free)	Dynamic compressor (centrifugal mainly)
Start/stop	Start/stop - be careful with overheating of motor at frequent starts	
Pressure relief	Pressure relief, or bypass - outdated	Pressure relief - outdated
Modulating, or inlet throttling	(not applicable to isochoric compressors e.g. "roots" type)	Inlet throttle (butterfly valve)
Vane control		Inlet guide vanes
		(Variable outlet) diffuser vanes
Load/unload	Load/unload, or pressure relief with throttled inlet	Load/unload (pressure relief with throttled inlet) at zero flow still 20% of full load power
Variable speed	Variable speed	Variable speed (allows controlling flow at constant pressure)
Other	Variable discharge port (lubricated screw only)	
	Suction valve unloading (reciprocating only)	

Master controller

Apart from flow control methods employed at compressor package level, part load can also be handled at system level: Larger compressor stations, comprising multiple compressors, may benefit from a master controller or scheduler that control the operation of the individual compressor packages. Well-known examples for a large system with a fluctuating air demand is operating fixed speed compressors for base load operation, and fill in the fluctuations above base load with a variable flow compressor[157]. Of course such a set-up requires thorough analysis of the system's exact flow profile and flow distribution to determine the time each compressor will operate in a certain condition, e.g., unloading, blowing-off or operating near design capacity, to be able to identify the optimal working points of the individual units.

This technology however by default exceeds the product boundaries and crosses over to the system level.

4.6 Heat recovery

As air is compressed it heats up. In principle this heat can be recovered and used for processes that otherwise would have required energy, such as space heating, water heating, process heating, drying, etc. Another form of heat recovery is applied in "heat-of-compression" dryers (see also section 3.4.3 on dryers).

4.6.1 Heat available, sources and temperatures

During operation energy losses of electric motors, transmissions and electronic components result in heat build-up under the sound canopy of the compressor. Other mechanical losses and not perfectly adiabatic parts and components also add to this heat build-up.

As many components, and the electric motor in particular, are usually not specified to operate in conditions exceeding 40ºC, this heat is removed.

Secondly, there is the heat of compression itself. The absolute, thermodynamic, temperature of this heat depends on the pressure ratio and on the ratio of the specific heats (gas specific).

When calculating back to the actual temperature of the air at the discharge, it is obvious that the efficiency of the compression process also influences the temperature at the outlet.

Equation 13 Calculation of thermodynamic heat

$$\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \Rightarrow T_{2s} = T_1 * \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$$

Where:

T_{2s} = thermodynamic temperature (K)

T_1 = temperature at inlet (K)

p_1 = pressure at inlet (Pa)

p_2 = pressure at outlet (Pa)

κ= ratio of specific heat

Assuming an ideal isentropic process, a pressure ratio of 1.5 and inlet temperature of 20ºC a temperature increase (difference inlet-discharge) of 36ºC can be calculated. A pressure ratio of 2 results in a 64ºC temperature rise, and a ratio of 8 bar to 238ºC temperature increase and for a pressure ratio of 12 the temperature increase is over 300ºC.

The outlet temperatures calculated above do not take into account cooling during the compression process (as is the case for lubricated machinery, or in case of intercooling between

[157] http://www.airbestpractices.com/system-assessments/end-uses/optimize-compressed-air-system-highly-fluctuating-air-demand

compressor stages). At higher compression ratios either one or both types of cooling are applied, lowering the outlet temperatures. Typical compressed air temperatures after the final stage of compression (before any aftercooler) are below 200ºC, maximum temperatures around 240ºC, depending on the pressure ratio.

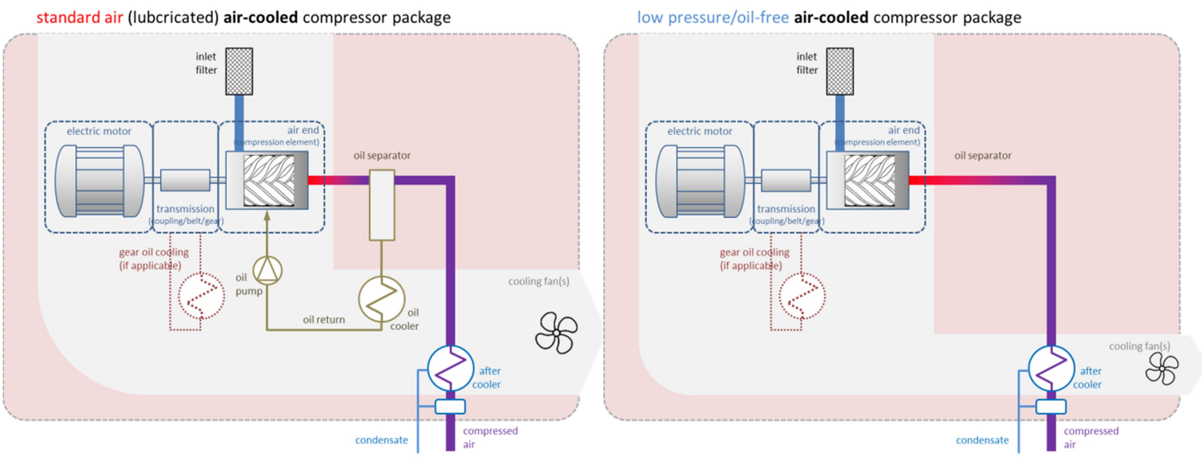
The heat of a **water-cooled** package may be dissipated to the environment by either of three main principles: open system without circulating water, open system with circulating water, closed system[158]:

- In open systems without circulating water, water is supplied by an external source such as municipal water mains, lakes, streams or a well. After passing through the compressor coolers, the water is discharged from the system as wastewater. While this system is generally easy and inexpensive to install, it can be expensive to run due to water usage or filtration and purification costs.
- Open systems with circulating water are primarily used when the availability of external water supply is limited. In this system, cooling water from the compressor is continually re-cooled inside a cooling tower. The re-cooling mechanism requires hot water to sprinkle down into a chamber as the surrounding air is blown through the water. In this system, the water gradually becomes contaminated by the surrounding air and must be regularly analysed and treated with chemicals to avoid algae growth. And during winter, when the compressor is not operating, the cooling tower must be drained or the water heated to prevent freezing.
- In the closed system with circulating water, the same water continually circulates between the compressor and some form of external heat exchanger which is in turn cooled either by external water or surrounding air. If cooled with external water—from a nearby lake or stream—a flat plate heat exchanger is used. If cooled by surrounding air, the air is forced to circulate through a cooling matrix of pipes and cooling fins and the water is treated with anti-freeze. If correctly implemented, a closed water system requires little supervision and has low maintenance costs.

  Additionally, energy recovered by means of a closed cooling system enhances the compressor operating conditions, reliability and service life due to an equalized temperature level and high cooling water quality.

Figure 49 and Figure 50 show schematically the cooling applied in both water- and air-cooled standard air (for reference) and low pressure / oil-free compressor packages.

Figure 49 Air-cooled 'standard air' and 'low pressure'/'oil-free' compressor packages



Note: In standard air (lubricated) packages. most of the heat of compression is transferred to the oil (some 70-80%), and some 4% is present in the compressed air. A cooling fan (or more)

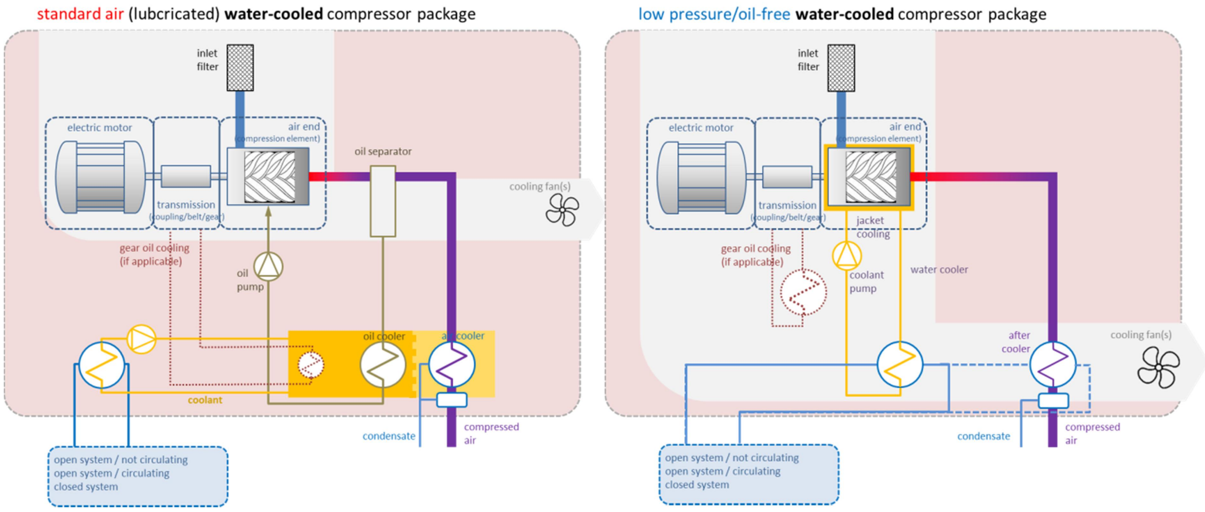
[158] http://www.thecompressedairblog.com/three-water-cooling-systems-and-heat-recovery/

draw air over heat exchangers for the oil and the compressed air, and simultaneously may draw cooling air over the motor and other heated parts.

For low pressure/oil-free air-cooled compressors, there is no oil and the air is therefore hotter (assuming the same state of change). A cooling fan draws air over an heat exchanger for the compressed air, and may simultaneously cool other components (electric motor, electronics).

By cooling compressed air also moisture (condensate) is removed.

Figure 50 Water-cooled 'standard air' and 'low pressure'/'oil-free' compressor packages

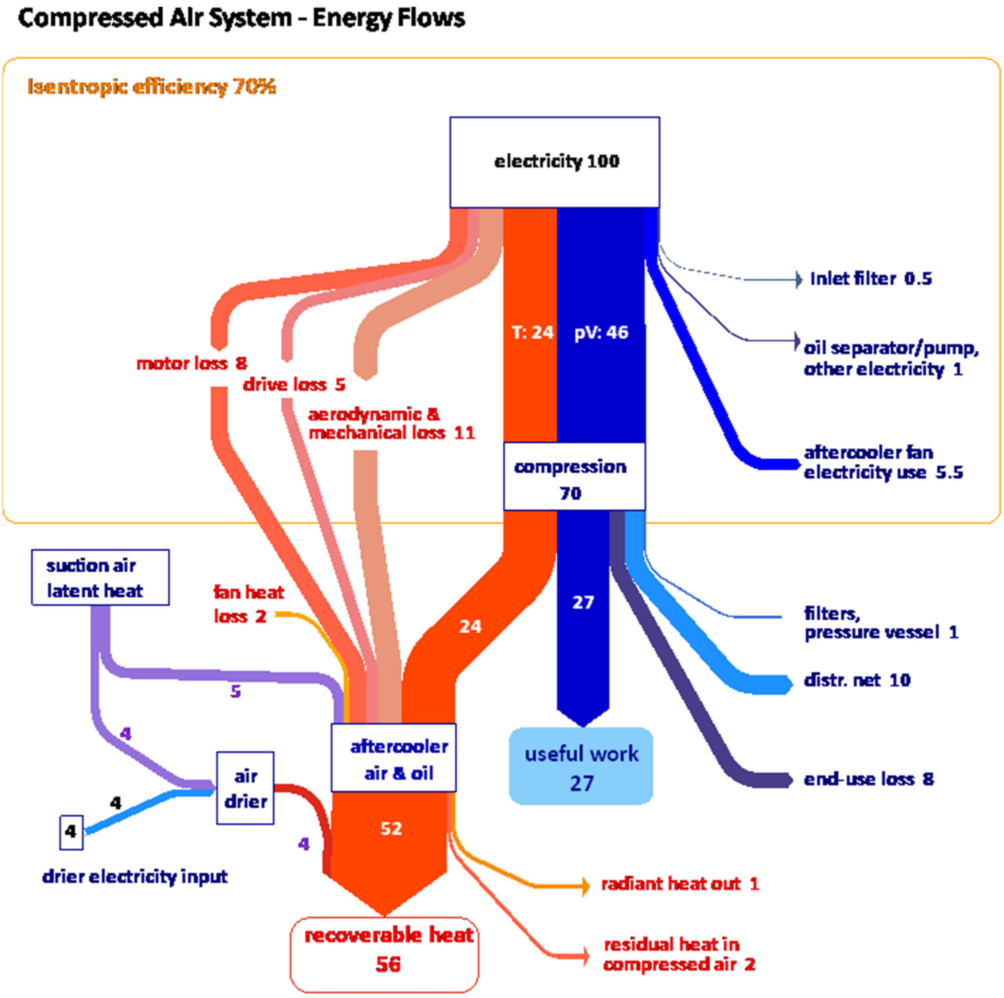


Note: In water-cooled standard air equipment, a circulating coolant removes heat from the oil and possibly the compressed air as well. As the oil has a high heat transfer coefficient and high heat capacity, the heat exchanger removing the heat from the oil and transferring it to a coolant can be quite small and may be integrated in the package. The heat of the coolant is then removed by a cooling system (using cooling towers etc.) .

In water-cooled low pressure / oil-free equipment the air end is cooled with a coolant (orange lines) and by inter-/aftercoolers for the compressed air (dotted line in figure) as cooling of just the air-end is usually not sufficient. The coolant is connected to a heat exchanger, usually located outside the package (extracting heat from compressed air requires relatively large heat exchangers) which expels the heat to the ambient. There may be multiple heat exchangers depending on the need to be able to switch between heat sources and/or heat sinks.

A dedicated fan removes the heat from other components, although there are examples of electric motors that are also liquid cooled.

Figure 51 Sankey diagram of heat flows and losses (Note: this is for standard air / lubricated)[159]



4.6.2 Feasibility of heat recovery

A detailed assessment of the actual heat recovery potential is notoriously difficult as each compressor application will have a different heat recovery potential. In general the potential depends on the right match between heat availability and heat demand (in quantities, temperature level, timing, continuity, distribution / transport, etc.).

Aspects that influence the possibilities for heat recovery are:

1. The medium in which heat is available (for low pressure and oil-free: air, water). Typically using heat from liquid media requires less external design effort.
2. The amount of energy available, determined by the mass flow, specific heat and (allowed) temperature difference between source and sink. This amount may be limited due to technical reasons: In lubricated compressors for instance, the return temperature (of the oil) should not drop below 80ºC to avoid condensation of water and associated damage within the compressor. The 'quality' of heat can be expressed using the Carnot-

[159] Elaboration by VHK, 2016.

factor. The available / allowed temperature level determines whether and where it can be used.

3. Availability and continuity of the heat supply and heat demand and the chronological synchronization. In particular variable flow packages may exhibit a varying pattern of heat availability. Insufficient continuity and/or synchronization may require additional investments in back-up systems and/or heat storage.
4. The spatial distance between heat supply and demand. With large distances heat losses increase, resulting in additional investments.

4.6.3 Heat recovery potential, limitations and drawbacks

There are situations or applications where recovery of heat is limited or not advised. The reasons may be:

1. Risk of condensation. As the dew point temperature decreases with increasing pressure, cooling of pressurized air will usually lead to condensation. This condensate needs to be removed, and condensation is further exaggerated when cooling the air even further. In certain pneumatic conveying applications, the cooling of air through heat recovery could lead to such dew point temperatures that condensation in the pipes could occur, which should be avoided especially when transporting media sensitive to moisture (sugar, cement, flour, etc.). Adding additional dryers would reduce the energy saving from heat recovery.
2. Additional pressure losses. Heat exchangers and, if necessary condensate traps, create additional pressure losses that increase the energy consumption of the package. The benefits of heat recovery should ideally overcompensate these losses.
3. Application considerations. In certain applications avoiding possible contamination is paramount (e.g. medical, food applications) and additional components may increase the risk of possible contamination. Furthermore, elevated temperatures help to "sterilize" the compressed air.
4. The grade of the heat. High grade heat (higher temperatures) can sometimes be directly used in industrial processes, but low grade heat (from packages with lower pressure ratio's and from package cooling) is often only usable for space heating, some drying processes and pre-heating of water. Transforming this low-grade heat to higher grades, to allow easier transportation and unlock more applications, is expensive as it requires additional equipment, lowering the return on the investments.
5. Distribution of heat sources and sinks. It is typical for smaller compressors, in the low pressure range, that they are close to the process they serve. Larger compressors may be installed in a dedicated "compressor room", often located further away from production facilities because of the noise. Recovering heat from many, distributed, heat sources, or remote locations, complicates the setup for minimal returns.

Assessing the potential for heat recovery of compressor packages in a detailed manner would vastly exceed the boundaries of the study scope as it would entail a mapping of EU-wide compressor applications and heating demands, including site conditions, and compressor characteristics. It is however known that the type of cooling and the type of flow control can have a major influence on the total amount of heat recovered. The approach below tries to quantify the potential by first looking at the initial potential for heat recovery.

Assuming that 4% of input energy is retained in the compressed air, when leaving the package and some 6% is lost through radiation and other unrecoverable heat sources, a starting potential of 90% has been defined for all categories.

As variable flow categories will show variations in amount of heat available, these categories have been corrected by a factor of 80%.

Air-cooled equipment is assumed to be used for space heating, requiring relatively simple ducting and controls. Water-cooled equipment requires a more extensive approach to heat recovery, sometimes by using additional heat exchangers. A loss factor of 80% is assumed for water-cooled equipment categories[160].

This results in an overall (very simplified) heat potential for the flow categories ranging from 58% to 90%[161]. Differences in heat recovery potential between different types of compressors (rotary positive displacement, single- or multi-stage turbo, etc.) have been ignored for simplicity.

Table 61 Heat recovery potential by flow control category

Heat recovery potential (supply side)	Initial HR potential	Losses due to variable flow	Losses in components	HR potential
LP_WFCR	90%	80%		72%
LP_LFCR	90%	80%		72%
LP_ZFCR	90%			90%
LP_ZFCRpeak	90%			90%
OF_WFCR/air	90%	80%		72%
OF_WFCR/water	90%	80%	80%	58%
OF_LFCR	90%	80%		72%
OF_ZFCR/air	90%			90%
OF_ZFCR/water	90%		80%	72%

In an assessment of savings through heat recovery, this potential has to be coupled with an assumption of how much of this potential is actually achieved in the field (see Task 7).

4.7 Performance assessment

One of the most important tasks in this second Lot 31 preparatory study is to map the performance of the equipment within scope.

The next two sections describe the approaches that have been applied.

4.7.1 Data retrieval from brochures, websites, etc.

A logical place to start this mapping and benchmarking exercise is by consulting the publicly available data.

The authors have collected performance data of 5276 working points of compressors. A working point means a combination of volume flow rate, discharge pressure and isentropic efficiency. All this data was extracted from manufacturers websites, product brochures and what else was available.

The 5276 working points do not represent 5276 individual models. Models equipped with a variable speed drive were covered/described by multiple entries (each entry or working point is a combination of volume flow, pressure and power input).

Including in this assessment is data published as CAGI data sheets. This data is independently verified, but as it turned out, CAGI data sheets are only available (status Summer 2015) for an

[160] See: http://www.chemicalprocessing.com/articles/2016/recover-heat-from-air-compression/?show=all, which mentions a heat exchanger efficiency of 90%.

[161] See: http://www.chemicalprocessing.com/articles/2016/recover-heat-from-air-compression/?show=all, which gives as rule-of-thumb that VSD compressors allow some 75% recovery. In the present study it was set at 80%.

extremely limited number of products within the scope of the study (some tooth, lobe and oil-free screw compressors). All other CAGI data is related to oil-injected/-lubricated equipment, which are outside the scope of the assessment.

The data collected allowed categorisation according:

1) Product identifier;
2) Technology type;
   a) Note: although the study approach is in essence 'technology-neutral, there may be applications that are very much linked to (characteristics of) certain technologies. History has shown that in specific cases regulations applied at the level of technologies rather than function or service [162]. Therefore it is preferred that the data collection contains information on technology.
3) Performance data:
   a) discharge pressure;
   b) volume flow rate;
   c) (package) input power;
4) Cooling type (air cooled, water cooled) if information was available.

The data points collected were distributed over the application ranges and technologies as shown in the tables below.

Table 62 Number of working points collected for both application ranges, by technology

Application range / Technology	Low pressure	High pressure	Total
Turbo	**404**	**0**	**404**
single stage	62		
multi stage (inline)	175		
side channel (regenerative blower)	167		
Positive displacement	**3950**	**922**	**4872**
piston	28	90	
lobe	2118		
screw	1689	758	
vane	115		
scroll		41	
tooth		33	
Total Turbo + PD	**4354**	**922**	**5276**

When looking at data points by volume flow classes (flow categories) it can be seen that certain technologies are more prominent in smaller volume flow classes (side channel, piston, vane), whereas others are more present in larger flow classes (lobe, screw, turbo).

[162] Regulation 327/2011 for fans introduced different requirements for types of fans, and so did Regulation 547/2012 on pumps. This is not meant as a recommendation for basis of possible regulating of low pressure and/or oil free compressors.

Table 63 Number of working points collected for the low pressure range, by volume flow category and technology

Technology / **Volume flow category (l/s)**	**Turbo**			**Positive displacement**			
	single stage	multi stage (inline)	side channel	piston	lobe	screw	vane
2.5							9
7.5			2		10		5
15			12	10	39		20
30			25	14	96		15
60	1		51	4	247	40	32
120	5		55		396	162	32
240	11		21		429	372	2
480	6		1		359	450	
960	12	24			349	379	
1920	19	61			174	258	
3840	8	90			19	28	
	62	175	167	28	2118	1689	115

Table 64 Number of working points collected for the 'oil-free' range, by volume flow category and technology

Technology / **Volume flow category (l/s)**	**Positive displacement**			
	piston	screw	scroll	tooth
2.5	15		8	
7.5	14		8	
15	32		12	
30	23	8	11	5
60	6	74	2	16
120		195		12
240		283		
480		156		
960		42		
totals	**90**	**758**	**41**	**33**

CAGI verified data represented 529 entries (some 10% of the total of entries), but was limited to high pressure 'oil-free' mostly (91% of 529 entries). The CAGI sheets originate from just three manufacturers, respectively representing 64%, 34% and 1% of the 529 entries. The technologies in the CAGI dataset were limited to tooth, lobe and screw OF compressors with respectively 6%, 9% and 85% of these 529 entries.

As stated, efficiency is based on work according the isentropic reference process, and the overall (basic) package electric input power (including motor drives, excluding driers or dehumidifiers).

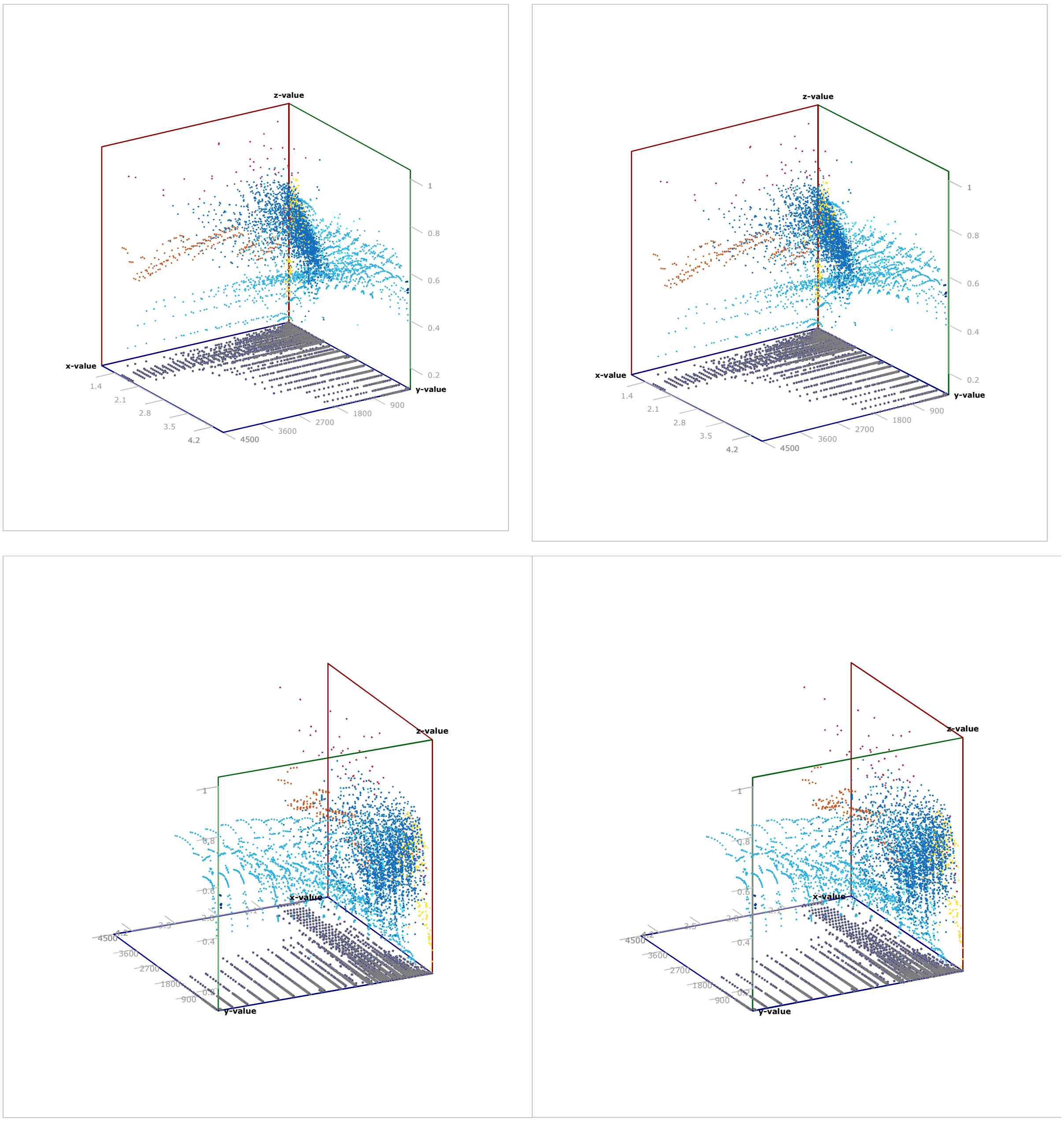
All efficiencies are calculated on the basis of package input power. Where only shaft power or nominal motor rating was given, values have been converted to package power.

Presentation of data

The data collected was used to draw 3D scatterplots [163] with efficiency (calculated as isentropic efficiency) at the Z-axis, volume flow as X-axis, and discharge pressure as Y-axis. The colours of the dots represent compressor technology. The resulting 'data clouds' could then be interpreted to show the relation of efficiency by operating conditions (flow vs pressure) and technology.

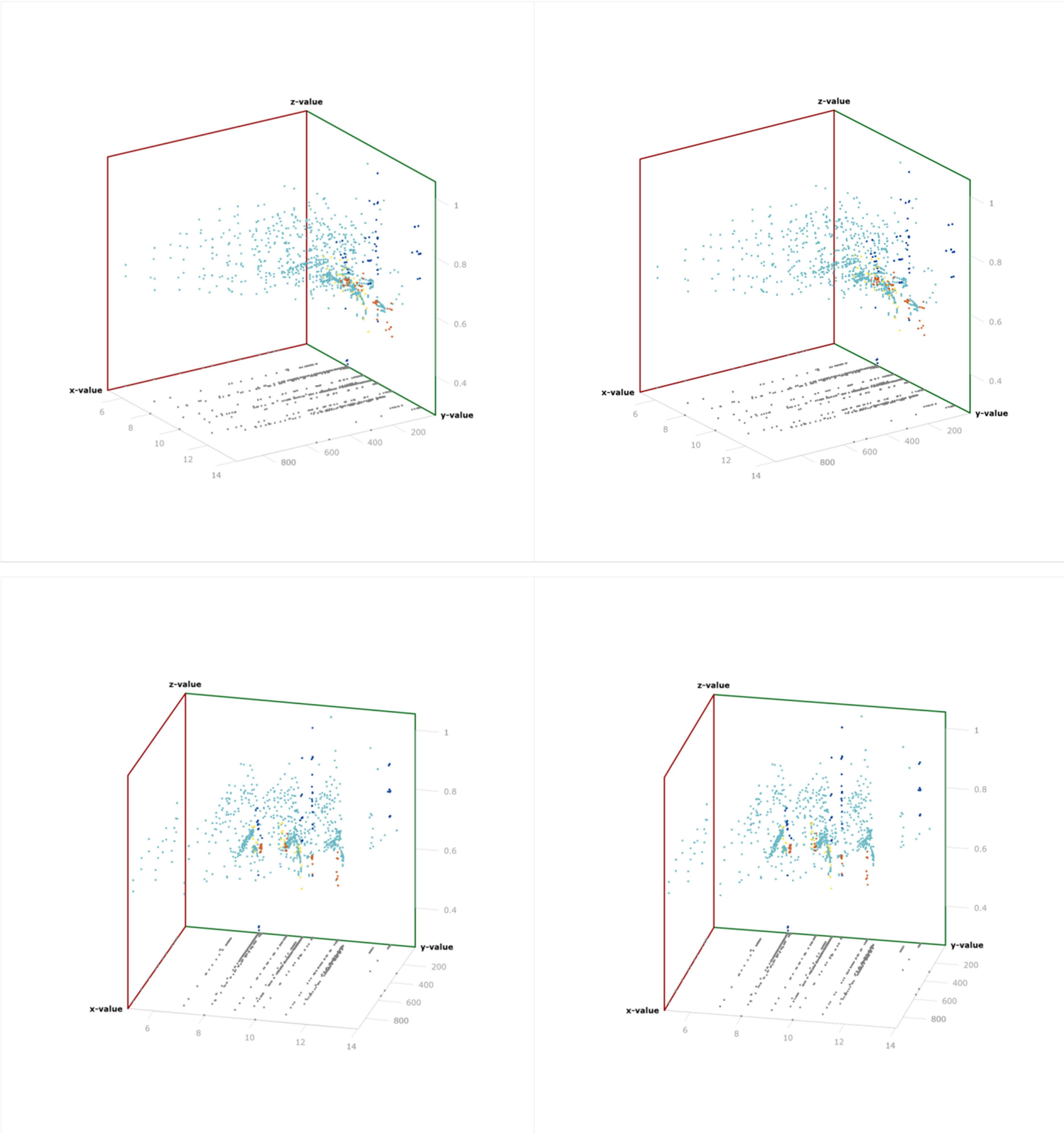
[163] 3D plot created by software from Gabor Doka [http://www.doka.ch/Excel3Dscatterplot.htm]

Figure 52 3D scatterplot of efficiency of low pressure compressors (x=vol. flow, y=pressure, z=efficiency)



Type	colour (code)	Remarks	Type	colour (code)	Remarks
piston	1	few entries, close to the max. pressure threshold	liq.ring	7	
lobe	2	very visible, but only in lower pressure range	axial	8	
screw	3	largest spread, also in higher pressure ranges	single stage	9	highest efficiencies, present in lower pressure range
vane	4	very few entries, at lower pressure range	multi stage (inline)	10	present in low pressure range
scroll	5		integrally geared	11	
tooth	6		side channel	12	close to origin, low pressures, low volumes

Figure 53 3D scatterplot of efficiency of oil-free compressors (x=vol. flow, y=pressure, z=efficiency)



Type	colour (code)	Remarks	Type	colour (code)	Remarks
piston	1	few entries, close to the min. flow threshold	liq.ring	7	
lobe	2		axial	8	
screw	3	largest spread, also in higher pressure ranges	single stage	9	
vane	4		multi stage (inline)	10	
scroll	5	very few entries, at lower flow range	integrally geared	11	
tooth	6	very few entries, at lower flow range	side channel	12	

The lower efficiency at lower volume flows (for instance: quite visible for positive displacement type compressors) has several reasons: Increasing (relative) importance of leakage and frictional flow losses, machining tolerances not scaling down with size, lower efficiency of smaller electrical motors or drive systems, lower efficiency of drives systems at lower load (speed and/or torque), mechanical losses not scaling down with size or input power, practical limitations to increase rotational speed in proportion to size reduction etc.

Please note that secondary performance parameters, such as behaviour at part load or at changing operating conditions are not reflected in these figures (see section 4.5.2.4 on 'Weighing'). Nor does the figure include assessment of economics.

The figures are for illustration only.

Issues

However, there are serious issues with respect to the data collected in this way:

1. The discharge pressure listed in data tables in brochures, websites, etc. may not be the actual discharge pressure used for establishing the flow rates. Example: a manufacturer may state products are designated as "7.5 / 10 / 13 bar" in the presentation table, but in the fine print, it is stated that free air delivery (FAD) is measured at working pressures of 7 / 9.5 / 12.5 bar. Where possible this was taken into consideration, but it is possible that not all manufacturers supplied this information.
2. In data sheets of manufacturers often the maximum discharge pressure and maximum volume flow rate are specified. These values do not necessarily correspond to the same operating point. Using these values for calculating the energy efficiency can lead to (far too high) efficiency values.
3. For a considerable number of entries the intake air pressure is not given. Even if 1 bar is stated, it is often not known whether this is atmospheric pressure (1.0325 bar(a) or 103 250 Pa) or simply 1.00 bar = 100 000 Pa.
4. For a vast number of entries the intake air temperature is not given. This may affect the (calculation of) volume flow rate. Where 'FAD' is stated this is mostly assuming intake air of 20ºC, but if Nm^3/s is stated, it may mean intake air of 0º C. The difference is almost 10% of the calculated volume flow rate as (assuming no influence of humidity and atmospheric pressure of 1.0 bar(a)) at inlet: $q_N = q_{FAD} * 0.92$ where q=volume flow rate in m^3/s.
5. Intake air humidity is usually not provided. It is assumed the data presented is for zero moisture, but this is rarely indicated.
6. For a vast number of entries the package power requirement is not given. Manufacturers often only state the nominal power of the motor. This is understood to be the motor shaft power and not the power absorbed by the motor at input terminals. Sometimes the shaft power of the air-end is given. Rarely the total package power is given.
7. The few CAGI data entries show that the total package power (of screw compressor packages) is usually higher than motor rating in case of high pressure compressors. But for certain low pressure compressors the package power may be lower than the motor rating. The difference between motor rating and package input power can exceed 20% according some CAGI verified models.
8. Even if package power is stated it is not known which components (or losses) are included/excluded in the package assessed. In many cases the fans supplying cooling air to the compressor are included in package power of air-cooled equipment, whereas for water cooled compressors, the water pump circulating the cooling fluid is not included in the package power requirement[164].
9. For a number of entries the package power is only given for 60Hz. In the EU the grid is at 50Hz, which results in less rpm and lower volume flow rates, but also lower power

[164] In principle the pump can be included in the basis of the internal differential pressure over the heat exchanger, and a default circulator efficiency (as is done in seasonal performance of ground source heat pumps).

input. Values based on 60Hz operation should be corrected for 50 Hz operation. The presence of data entries based on 60 Hz data is limited.

10. For machines with a variable speed drive or other variable flow mechanisms, the package power input may exceed the nominal power rating of the motor at full load conditions. But in part load conditions, the package input power should be well below the nominal rating of the motor. Reduced package power at part load conditions could not always properly be taken into account.
11. Certain data could only be extracted by interpreting printed graphs and curves.

In order for performances to be comparable the data has to refer to:

- performance recalculated to identical standard inlet conditions;
- identical, or at least functionally comparable and realistic, package hardware ("basic package");
- allow proper consideration of part load operation.

4.7.2 Data collection based on manufacturer survey

The industries involved in the study as stakeholder recognised the drawbacks of the above data collection effort and organised an internal data collection effort. The benefit of this collection is that the above issues (standard inlet conditions, basic package, consideration of part load performance) could be solved.

The survey however had its limitations in that the industries were not allowed to collectively collect and share with third parties data related to sales and performance because of anti-trust laws. Even on individual level manufacturers in general remained reluctant to share certain information because of commercial and technical sensitivity of this information.

Standard Inlet Conditions

All data was collected from testing of products in accordance with ISO 1217 for positive displacement compressors and ISO 5389 for dynamic (turbo) compressors. Values have been recalculated to the standard inlet conditions defined below (based on ISO 1217:2009, Annex F):

- inlet air pressure: 1 bar(a), or 100 kPa;
- inlet air temperature: 20°C;
- inlet air moisture: 0% RH;
- temperature of coolant: 20°C;
- for oil-free only: max. temperature difference outlet- inlet: < 25K.

As an extra condition for the low pressure range it is proposed to introduce as standard inlet condition (or operating condition) a maximum temperature difference over the inter-/aftercooler of maximum 25 K[165].

Depending on the volume flow control range specified by the manufacturer, the number of working points to be assessed ranges between 3 to 9.

Basic package

Also important for comparing compressor performances is the set-up of the compressor package of which the performance is assessed: what components need to be present, included in the package, are allowed to be added or are required to be excluded/disconnected.

As the use of certain components is sometimes inherent to the use of certain technologies, this introduces extra complications.

[165] For side channel blowers and rotary vane compressors in low pressure applications an inter-/aftercooler is usually not required.

The basic package includes (where relevant).:

- Motor, air-end and transmission (where relevant);
- Controls and components for reliable and safe operation, such as;
    - Compressor controller;
    - Anti-surge valve;
    - Flare valve (especially relevant if inlet throttling takes place);
    - Shutdown valve;
    - Blowdown valve;
    - Blow-off valve[166];
    - Discharge check valve;
    - Relief valve;
    - Purge valve;
    - Suction scrubbers;
    - Vent valve.
- Air inlet filters;
- Intercoolers and aftercoolers. Oil coolers are not required for the oil-free application range by default, and practically not necessary for the low pressure range either (as there are no oil-flooded compressors present in that range).
- Pulsation vessels or dampeners. These are required to provide a buffer in the compressed air line so as to reduce the air pulsation. Dampeners are used to reduce working environment noise to acceptable levels. The functions may be combined in a single component. Such components may also act as intercoolers and moisture removal.
- Silencers, to suppress acoustic noise;

Possible components (to be included as 'optional component' or as 'allowed feature') are:

- variable speed drive;
- inlet throttling devices;
- Inlet guide vanes;
- Diffuser guide vanes;

Not part of the basic package, and thus proposed for removal, disconnection or compensation for establishing the performance are:

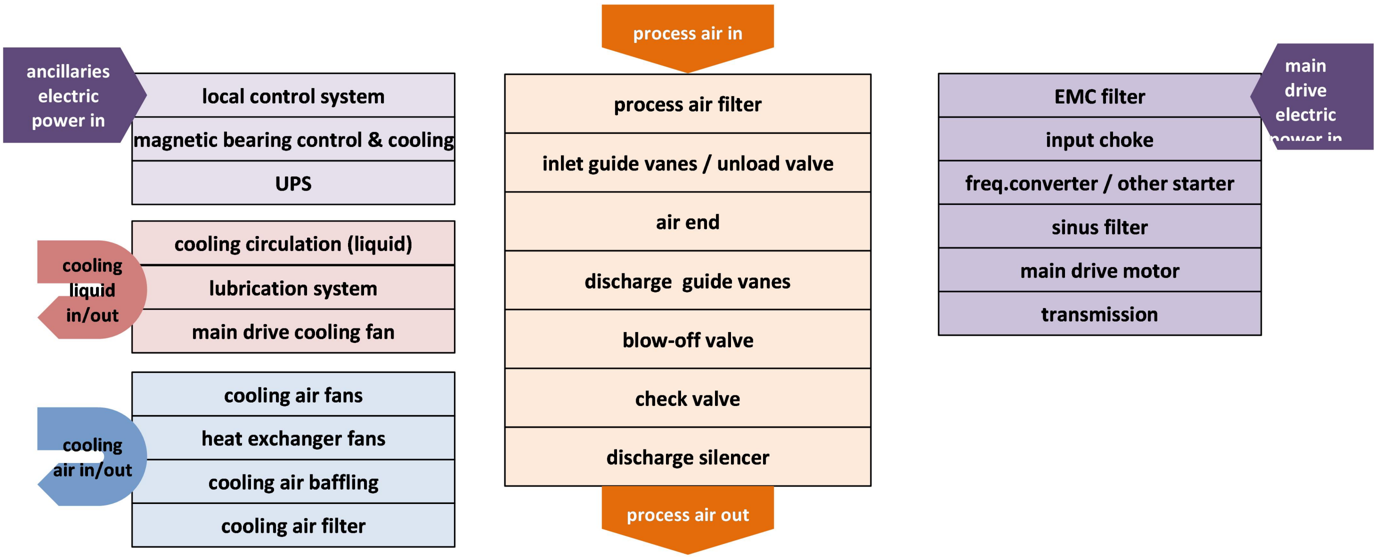
- Air Dryers for further removing moisture from compressed air (after aftercooler condensate traps).

As 'heat of compression' dryers are an obvious choice for combination with certain oil-free compressor designs, the 'system level' benefits of this option will not show in the assessment of performance data.

- Air receiver tanks.

[166] The "blow off valve" is used to partialize the discharged flow when the unit cannot reduce its (rotational) speed any more.

Figure 54 Proposed basic package



Flow Control Range categories

As explained in Task 3 "Users" the applications of compressors are categorised according flow control range and whether peak pressure can be handled. The categorisation is wilfully not based on specific technologies in order to remain technology neutral. The categorisation is mainly based on customer preferences on the functionality of the product: If he/she has a highly fluctuating air demand, products in the WFCR category would be the preferred category of products to look for.

Table 65 Flow control range categories

	Low pressure	**Oil-free**
WFCR	Wide Flow Control Range (minimum flow >50% of maximum, for at least one specified pressure)	Wide Flow Control Range (minimum flow >60%, for at least one specified pressure)
LFCR	Limited Flow Control Range (minimum flow ≤50% of maximum at each specified pressure)	Limited Flow Control Range (minimum flow ≤60% of maximum at each specified pressure)
ZFCR	Zero Flow Control Range	Zero Flow Control Range
ZFCRp	Zero Flow Control Range with pressure peak capability	

Basis for performance assessment – entire allowable working range

In the first Lot 31 preparatory study, data was collected for a single rated pressure. For fixed speed machines this is a single point on the performance curve. For variable speed machines, a weighing was applied for the efficiencies at three working points at the rated pressure.

The approach for assessment of efficiency using more than a single rated point is that a male fide manufacturer could sell compressors (that meet the requirements in that single rated point) for operation at a different than rated pressure in which it would not meet the minimum requirement. A bona fide manufacturer would aim to meet the requirement in this other operating condition as well.

Therefore it was suggested to base the performance assessment on the entire allowable working range of the product.

Weighing points

Virtually all compressors placed on the EU market allow operation within a certain pressure range (from minimum to maximum) and within this a certain volume flow range. The operating range for fixed speed machines is therefore not a single point, but a <u>curve</u> in a volume flow / pressure diagram. For a variable speed compressor it is an <u>area</u>.

As it is impossible to know for each compressor placed on the market, at which operating point(s) it will function, it was decided to apply a weighing whereby the performance at the middle operating point receives the largest weight and the performance at operating points further away from the centre of the declared operating range receive a smaller weight.

Knowing that the 'maximum' volume flow rate depends on the discharge pressure, it is defined that "100% volume flow rate" means the respective maximum volume flow rate at the respective discharge pressure.

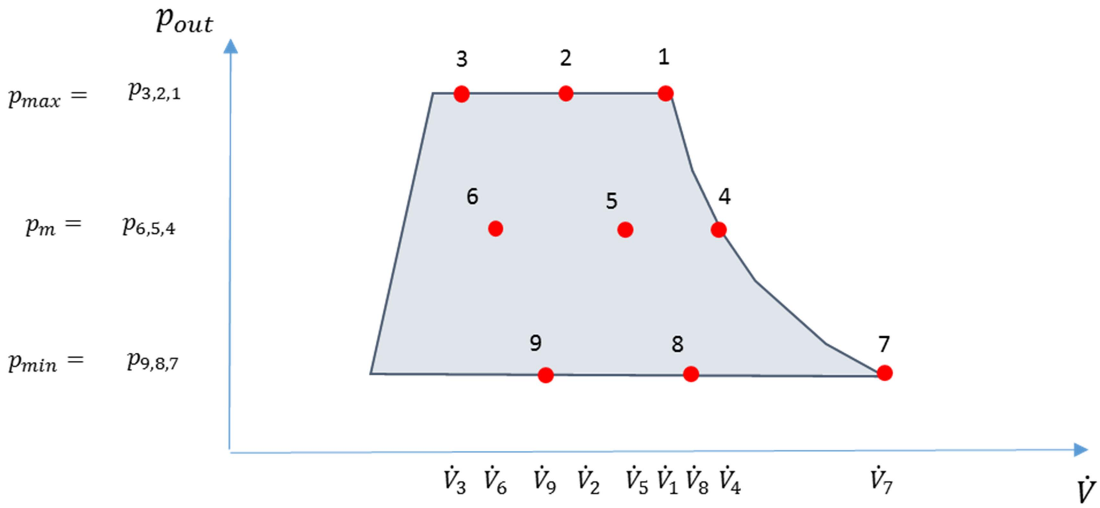
Any partial volume flow rate, e.g. 50% volume flow rate, refers to a percentage of the maximum volume flow rate at the respective discharge pressure.

For machines with a "wide flow control range" it means that the minimum flow rate is equal to or less than 50% (for low pressure) or 60% (for oil-free) of the maximum volume flow rate for the entire pressure range, e.g. from p_{2max}, p_m and p_{2min} pressure:

1. the manufacturer declares a minimum and maximum pressure (p_{min}, p_{max}). From this follows a median pressure (p_m, the simple average of min/max pressure);
2. the working points for which the power requirement (and the efficiency) shall be established are for each discharge pressure a flow rate of 100%, 70% and 40% of the maximum volume flow rate of that pressure.
3. if the 50% of maximum volume flow rate cannot be achieved, the minimum flow rate (at least 60% according definition of large flow control range) for that specific pressure shall be used.

Most positive displacement equipment has a wide flow control range

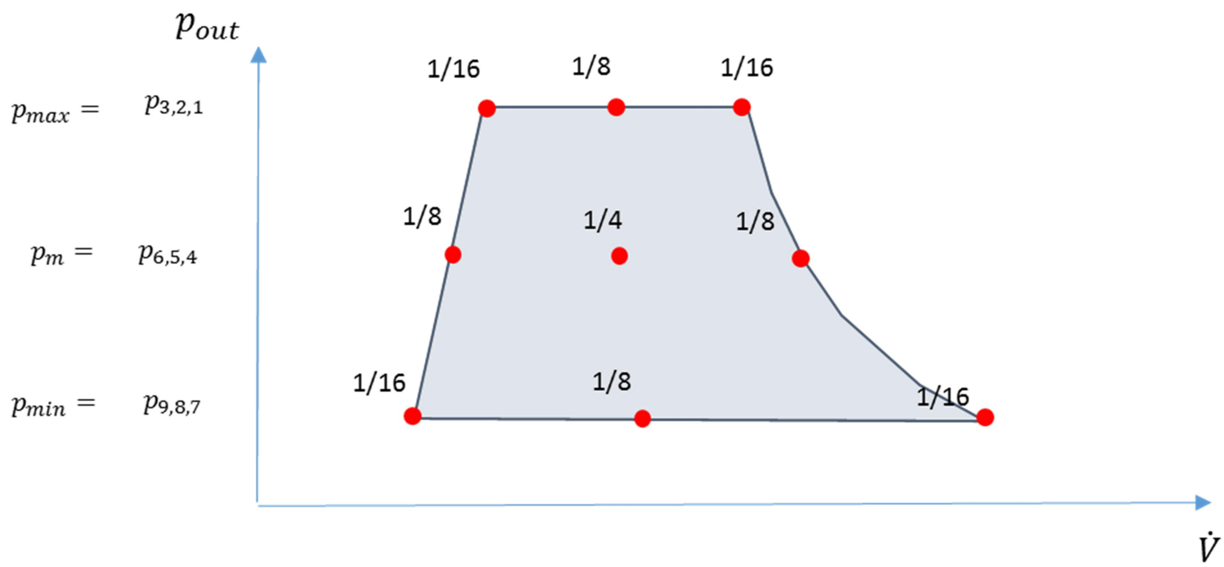
Figure 55 Location of data points for a wide flow control range compressor



For machines with a limited flow control range it means that the minimum flow rate is (for low pressure equipment) more than 50% of the maximum volume flow rate for that same pressure, over the entire pressure range (for oil-free the limit pressure is 60%),:

1. the manufacturer declares a minimum and maximum pressure (p_{min}, p_{max}). From this follows a median pressure (p_m, the simple average of min/max pressure);
2. the manufacturer declares a minimum and maximum volume flow rate for the minimum, maximum and median pressure (p_{min}, p_{max} and p_m). From this follows a median volume flow rate (V_m, is simple average of min/max volume flow rate), for each of the three pressures;
3. the working points for which the power requirement (and the efficiency) shall be established are, for minimum, maximum and median discharge pressure, the minimum, maximum and median flow rate of that pressure. This results in 9 working points;.

Figure 56 Location of data points for a limited flow control range compressor



The average isentropic efficiency of the model shall be calculated as the weighted average of efficiencies of all nine working points, p1V1 to p9V9, weighted as shown below.

Table 66 Weighing of nine data points p1,V1 to p9,V9

	V1	V2	V3	V4	V5	V6	V7	V8	V9
p1	1=1/16								
p2		2=1/8							
p3			3=1/16						
p4				4=1/8					
p5					5=1/4				
p6						6=1/8			
p7							7=1/16		
p8								8=1/8	
p9									9=1/16

¼=25%

1/8=12.5%

1/16=6.25%

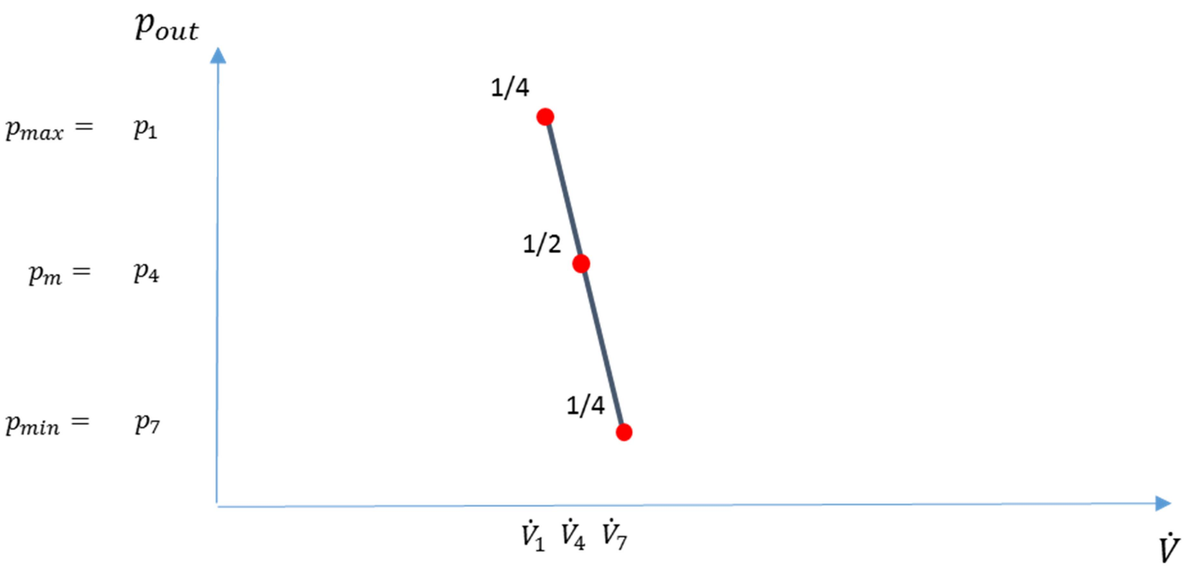
For machines with zero flow control range (zero flow control range means that the flow rate cannot be reduced intentionally irrespective of pressure):

1. the manufacturer declares a minimum and maximum pressure (p_{min}, p_{max}). From this follows a median pressure (p_m, is simple average of min/max pressure). The volume flow rate follows from the pressure assessed;
2. For each of these three points the manufacturer establishes the power input.
3. The average efficiency shall be calculated on the basis of these three points according the weighing below.

Table 67 Weighing of three data points p1,V1 to p7,V7

	V1	V4	V7
p1	1=1/4		
p4		2=1/2	
p7			3=1/4

Figure 57 Location of data points for a zero flow control range compressor



For 'zero flow control range with pressure peak capability' (only for low pressure applications – see Task 3) the same calculation as for 'zero flow control range' (without pressure peak capability) shall be followed.

The data collection based on brochures and websites will not allow a consistent and harmonised weighing as the extracted working points may be very different between models, technologies and manufacturers. A harmonised approach is needed so that weighing is consistent and a single 'typical' efficiency for each model can be established. For this the input of manufacturer data is indispensable.

Result of survey

The survey resulted in the data presented in the table below.

Table 68 Results of data survey, Pneurop, 21 November 2016

Survey parameter	LP_ZFCR	LP_ZFCRpeak	LP_LFCR	LP_WFCR	OF (all)
avg. power (kW)	8.9	23.5	58.4	29.4	37.3
avg. operating time (h/a)	3644	2688	3902	3943	3655

avg. load factor (-)	0.78	0.62	0.9	0.89	0.84
avg. product life (a)	8.8	13.2	12.2	12.0	12.7
avg. efficiency (-)	28.6%	47.9%	40.0%	50.5%	48%
total sales 2015 (#)	13638	5378	593	2888	9335
total energy consumption for sales 2015 (TWh/a)	0.35	0.21	0.12	0.3	1.07
eBAT (D-value)	23	13.4	22.8	14.4	28.9
eWAT (D-value)	-14.3	-21.1	-42.1	-18.8	-23
configurations assessed (#)	1542	2002	193	1168	393

Furthermore, for all flow categories (LP and OF_ZFCR|A, -|W, OF_LFCR and OF_WFCR|A and -|W) tables were provided with information on efficiencies per cell (see Table 70 and), eBAT and eWAT, plus curves showing the energy savings if a minimum energy efficiency requirement was imposed, plus the effect of this on sales.

This source data required further elaboration by VHK to:

1) fill in parameters per oil-free flow category (see Task 2 for sales, power and product life, Task 3 for operating hours, load factor).
2) to correct sales weighted values of efficiencies of the low pressure range categories to values that are consistent with absorbed power (that of oil-free were already elaborated by VHK only).
3) to calculate (average) flow and pressure applicable to given average power input (for all flow categories).

This assessment resulted in the following data described the performance as used in the subsequent Task reports (Task 5, 6 and 7).

Table 69 Power, flow, pressure and efficiency (average, worst, best) per flow category[167]

	Power (kW)	Flow (l/s)	Pressure (bar(a))	Average efficiency	Worst efficiency		Best efficiency ("BAT")		Configurations
					D-value (as %)	(derived eff.)	D-value (as %)	(derived eff.)	
LP_WFCR	29.4	551	1.3	55.99%	-19%	48%	14%	62%	1168
LP_LFCR	58.4	646	1.7	67.66%	-42%	54%	24%	75%	193
LP_ZFCR	8.9	125	1.3	38.24%	-14%	30%	23%	52%	1542
LP_ZFCRpeak	23.5	412	1.3	51.73%	-21%	42%	13%	58%	2002
OF_WFCR/air	26.3	49	8.0	55.28%	-12%	50%	17%	63%	45
OF_WFCR/water	162.3	376	8.0	66.37%	-21%	59%	17%	72%	53
OF_LFCR	185.0	427	8.0	64.31%	-30%	54%	35%	77%	70
OF_ZFCR/air	13.7	26	8.0	52.57%	-17%	45%	14%	59%	138
OF_ZFCR/water	80.4	198	8.0	69.29%	-17%	64%	30%	78%	85
LP_all	16.49			50.2%					

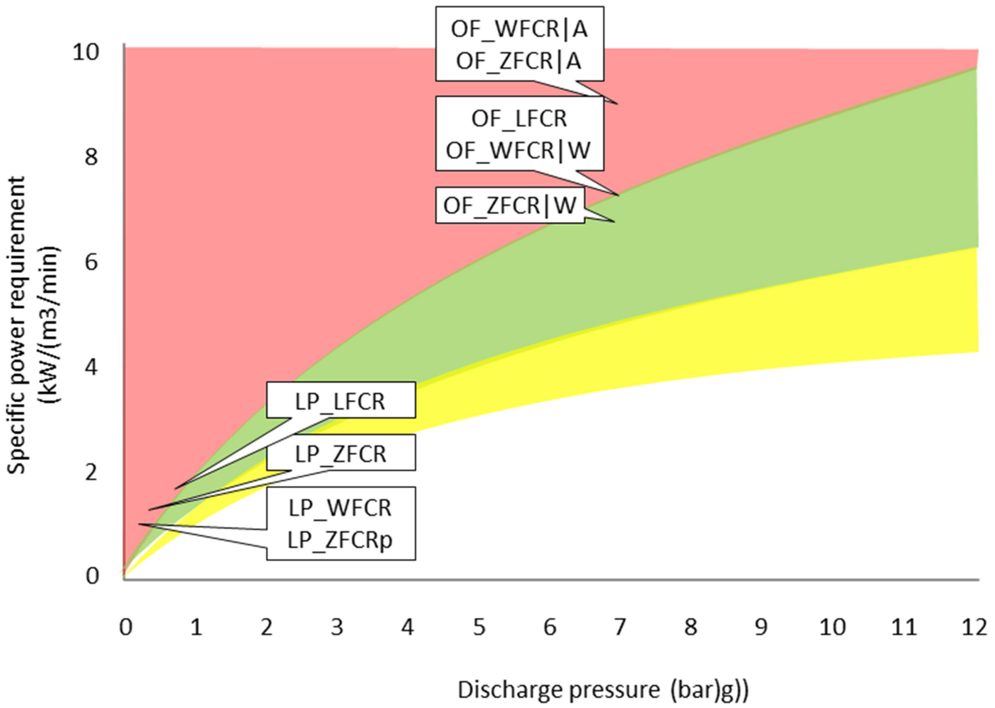
[167] Elaboration by VHK of data supplied to VHK in November 2016.

OF_all	37.33	62.2%

The above values are only valid for the power consumption of the specific flow control category.

The efficiencies that have been concluded appear to be consistent with literature regarding specific power demand.

Figure 58 Specific power requirement per flow category, plotted over generic graph [168]



Within a flow control category there are however large differences in efficiencies as equipment provides other flow rates at other pressures using other technologies. In reality the average efficiencies, when plotted on three axes (x= flow, y=pressure, z=efficiency) show a landscape characterised by hills and valleys (and empty spots where not enough sales were registered to allow processing of data). The variation of the landscape is primarily determined by the heterogeneity of the technologies present in that flow category.

[168] Energy efficiency in manufacturing systems, Sebastian Thiede, Springer Science & Business Media, 23 apr. 2012 - 198 pages, referring to Gloor 2000: Specific compressor power demand in kW for generating one m^3/min compressed air, depending on nominal system pressure (Gloor, 2000)

Table 70 Efficiencies of LP packages (average of configurations in cells defined by flow/pressure boundaries, average of which forms the x/y axis)

Pressure p_2 (bar(a))	Volume flow (l/s)									
LP_WFCR	**1.0**	**2.5**	**6.4**	**16.1**	**40.6**	**102.3**	**258.2**	**651.7**	**1640**	**4150**
1.1					28%	32%	40%	52%	58%	
1.3					34%	43%	52%	57%	61%	63%
1.5					42%	50%	57%	60%	63%	64%
1.8						56%	60%	63%	65%	65%
2.2							58%	61%		
2.6										
3.1										
3.6										
4.2										
≤5										
LP_LFCR	**1.0**	**2.5**	**6.4**	**16.1**	**40.6**	**102.3**	**258.2**	**651.7**	**1640**	**4150**
1.1										
1.3					26%	31%	46%			
1.5					32%	43%		68%	70%	
1.8								68%	70%	71%
2.2								63%		
2.6								63%		
3.1										
3.6										
4.2									73%	75%
≤5										
LP_ZFCR	**1.0**	**2.5**	**6.4**	**16.1**	**40.6**	**102.3**	**258.2**	**651.7**	**1640**	**4150**
1.1				19%	24%	30%	39%	47%		
1.3		19%	23%	24%	28%	37%	46%	50%	52%	
1.5		19%	25%	28%	32%	46%	52%	56%	56%	
1.8			28%	30%	32%	46%	55%	61%	62%	
2.2						42%	55%	61%		
2.6						51%	58%	60%		
3.1						54%	61%	64%		
3.6							63%	65%		
4.2										
≤5										
LP_ZFCRp	**1.0**	**2.5**	**6.4**	**16.1**	**40.6**	**102.3**	**258.2**	**651.7**	**1640**	**4150**
1.1				32%	40%	45%	48%	49%	51%	51%
1.3				37%	43%	48%	51%	53%	55%	55%
1.5				38%	43%	49%	51%	55%	57%	56%
1.8					43%	49%	51%	59%	61%	
2.2							59%	64%	67%	
2.6										
3.1										
3.6										
4.2										
≤5										

Table 71 Efficiencies of OF packages (average of configurations in cells defined by flow/pressure boundaries, average of which forms the x/y axis)

Pressure p_2 (bar(a))	Volume flow (l/s)								
OF_ZFCR|A	**1.0 l/s**	**2.5**	**6.1**	**15.2**	**37.6**	**93.1**	**230.5**	**570.8**	**1413**	**3500**
bar(a) 5.0										
6.1					51%	58%	64%	66%	67%	
7.2		44%	46%	47%	53%	60%	64%	67%	67%	
8.3				53%	54%	61%	64%	67%		
9.4										
10.6										
11.7										
12.8										
13.9										
OF_ZFCR|W	**1.0 l/s**	**2.5**	**6.1**	**15.2**	**37.6**	**93.1**	**230.5**	**570.8**	**1413**	**3500**
bar(a) 5.0										
6.1						68%	69%	72%	74%	
7.2						67%	70%	74%	75%	
8.3						67%	70%	75%	76%	
9.4							75%			
10.6										
11.7										
12.8										
13.9										
OF_LFCR	**1.0 l/s**	**2.5**	**6.1**	**15.2**	**37.6**	**93.1**	**230.5**	**570.8**	**1413**	**3500**
bar(a) 5.0										
6.1										
7.2								66%	80%	
8.3							60%	67%	81%	
9.4										
10.6										
11.7										
12.8										
13.9										
OF_WFCR|A	**1.0 l/s**	**2.5**	**6.1**	**15.2**	**37.6**	**93.1**	**230.5**	**570.8**	**1413**	**3500**
bar(a) 5.0										
6.1							62%			
7.2						55%	58%	61%		
8.3						56.4%	57.7%	60%		
9.4						60%	62%			
10.6										
11.7										
12.8										
13.9										
OF_WFCR|W	**1.0 l/s**	**2.5**	**6.1**	**15.2**	**37.6**	**93.1**	**230.5**	**570.8**	**1413**	**3500**
bar(a) 5.0										
6.1							66%	69%		
7.2						60%	64%	69%		
8.3						62%	65%	69%		
9.4						66%	69%	72%		
10.6										
11.7										
12.8										
13.9										

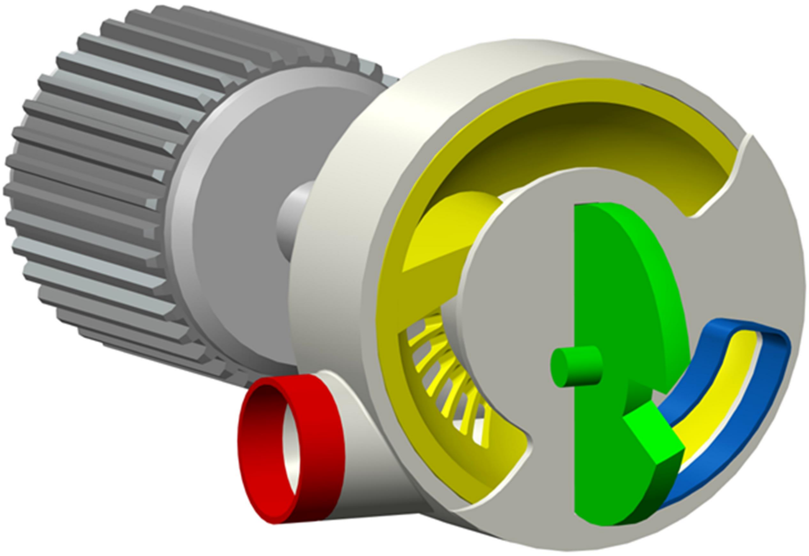
4.7.3 Technologies available on the market but not assessed

This section presents a few technologies that are available on the market, but the performance of which has not (or could not) be assessed.

Lontra Blade Compressor®

The Blade Compressor® was invented by British inventor, Steve Lindsey[169] and is best imagined as a piston and cylinder, but with the piston wrapped into a ring doughnut shape. A circular mechanism replaces the traditional 'up and down' piston technology and so the piston or "blade" always travels in one direction. This means that the compressor has an almost continuous cycle of inducing air the behind and compressing air in front, a unique oil-free geometry that minimises waste.

Figure 59 Blade compressor – illustration of working principle



The above figure is illustrative only as does not depict a real working machine.

The compressor has a constantly open intake port, without valves. As the piston or "blade" rotates, it induces a complete volume of air behind it until it reaches the starting point. As the blade passes through the disc it catches up the air induced in the previous cycle and compresses it in front, while inducing a new cycle of air behind.

This means that it has an almost continuous cycle of inducing air behind and compressing air in front, a unique oil-free geometry providing internal compression with very low leakage and low inlet and outlet flow losses that is quieter, smoother and highly efficient.

It comprises an internal rotor and outer casing, both with integral discharge ports, allowing the compressed air to discharge when they line up during the compression cycle.

Its unique sealing geometry and gas flow paths means that it can maintain efficient operation over a very wide range of air-flow. The compression process is oil free.

In site trials, Severn Trent Water reported 20% less energy consumption than traditional, comparator machines, and improved reliability. The design and geometry enable the air-end to be manufactured without the expensive tooling required for some other technologies.

The Blade Compressor® design can be adapted to work with any kind of gas or airflow equipment, from the compressor in a fridge or air conditioning system to the supercharger in a car engine. Lontra has applied the concept to deliver air pressures from 0.5 bar to 10 bar(g).

[169] Source: http://lontra.co.uk/technology/blade-compressor/ This technology was already mentioned in the first lot 31 study.

The technology is licensed to Sulzer, already producing turbo compressors for the municipal and regulated wastewater sector[170].

Ultra-high speed turbo compressor

Turbo compressor manufacturers have successfully applied the principle of reducing the impeller diameter whilst increasing the speed (tip speed remains constant) to increase the energy efficiency of their products.

One of the latest examples of this downsizing of impeller diameter is provided by CELEROTON which introduced on the market in September 2016 an ultra-high speed turbo compressor, running at up to 1 million rpm, equipped with gas bearings[171].

Allegedly (as the unit was not entered in the Lot 31 performance survey, nor independently verified data was available) the unit offers a pressure ratio of 1.65, and a mass flow of 17 or 24 g/s at a maximum isentropic efficiency of 59%. The rated maximum power is 0.7 or 1 kW. The size of the equipment is however just 530 cm^2.

The website mentions as main application areas:

- Oil-free air supply of fuel cells;
- Low-maintenance air conditioning and heat pumps with the highest performance (in stationary as well as mobile applications e.g. hybrid and electric cars);
- Mobile respirators and oxygen concentrators;
- Decentralised pneumatics (pressure and vacuum generation);
- High-tech blowers.

A regenerative blower in the same operating range has an isentropic efficiency (assuming zero flow control range, weighted over 3 points) of close to 30%, leading to a power consumption of almost 2 kW. The ultra-high speed turbo apparently uses half of that.

Prices and other details are missing and a comparison on total life cycle costs could not (yet) be made.

4.7.4 Technology not (yet) available

This section describes developments and technologies that are <u>not yet available</u> on the market and the performance of which is not known and/or cannot be compared to existing technologies.

Product/component level

Three-rotor screw

The well-known twin-rotor screw can also be constructed with three rotors (one male rotor in the centre, two female rotors at each side). Allegedly this design reduces deflection of rotors and the developer claims it is 5 to 10% more efficient than the twin-rotor design[172]. The 3-rotor design also balances thrust, which reduces bearing loads and gives a longer bearing lifetime. The 3-rotor design is apparently already in use in certain chiller compressors (refrigeration), but application, price and performance as air compressor is (yet) unknown.

Translating gear compressor

This compressor is essentially a rotary positive displacement compressor with an orbiting rotor (as in scroll compressors). The geometry is less complicated and the design offers variable

[170] Source: https://www.imeche.org/news/news-article/lontra-wins-compressor-funds and http://www.ingenia.org.uk/Ingenia/Articles/999

[171] http://www.celeroton.com/en/about-us/news/detail/launch-of-turbo-compressors-with-gas-bearings.html

[172] Information from: www.comptech-innovation.com

suction and bypass holes[173]. The inventor claims the total efficiency is comparable to that of a scroll compressor, at lower cost. The technology is not yet available on the market and actual price and performance is unknown.

Toroidal intersecting vane machine[174]

The toroidal intersecting vane machine is a positive displacement type technology, described in 1985. It received funding from US DOE for development (for fuel cell cars) from 2002 to 2006 but so far hasn't made it to the market. Current status of development is unknown.

Package level

Waste heat-to-power

Some 80% to 90% of the energy input of a compressor packages leaves the package in the form of heat. The actual maximum temperature available differs per technology and is some 200-300ºC for oil-free packages to 100-140ºC for low pressure packages. The waste heat is either transferred to air (air-cooled equipment) or to water (water-cooled equipment). Most of the heat (for low pressure or oil-free equipment) is available in the compressed air stream, a minor share is waste heat from the motor and drives (and oil coolers if applied).

It is possible to use this fairly low grade waste heat to drive a turbine for generating power. Usually this is accomplished through an Organic Rankine Cycle, whereby an organic fluid is evaporated using the waste heat (analogy to steam) and drives a turbine which drives a generator. Trilateral Flash Cycle (TFC) and the Partially Evaporating Cycle (PEC) also offer possibilities[175].

Maximum Carnot efficiency for a 95ºC process source and a 15ºC sink are close to 20% but actual efficiencies achieved by waste heat–to-power applications are much lower. The (thermal) efficiency of ORC-like cycles is some 2-20%, with the lower value applying to smaller equipment and/or lower temperatures.

TFC is simpler than ORC and has been under investigation for heat-to-power applications. For TFC it is expected that development of expanders that can cope with two-phase expansion may improve performance. At least one study[176] describes an expander composed of a pair of screw rotors allowing TFC cycles, which would form an interesting combination for manufacturers of such components for compressors.

However, the considerable extra costs (for extra heat exchangers, expanders, turbine) and extra volume (size of package may be doubled?) and the very limited gains make application of such technologies prohibitive.

No compressor packages that incorporate waste heat to power using ORC, TFC or PEC yet exist and no price or performances can be quoted.

Thermo-electric power

Thermo-electric cells convert waste heat to power. Until recently thermo-electric generators (TEG) required very high temperatures, suffered from low efficiencies, and costs for the material were high. But advances in material technology has led to TEGs that operate at lower temperatures, produce more power at reduced costs.

---

[173] Information from: http://www.flycarpet.net/en/TGCompressor#

[174] https://www.hydrogen.energy.gov/pdfs/review04/fc_41_bailey_04.pdf

[175] http://www.eng.usf.edu/~hchen4/Thermodynamic%20Cycles%20for%20the%20Conversion.htm

[176] Stian Trædal, Analysis of the Trilateral Flash Cycle for Power Production from low Temperature Heat Sources, Norwegian University of Science and Technology, Department of Energy and Process Engineering, June 2014.

For now, it appears that TEG are still too expensive for the relative small and low temperature waste heat available from most compressor stations, but for pipeline compressor stations, driven by natural gas turbines, TEG technology is already applied[177].

No air compressor, within the low pressure and/or oil-free scope, incorporating this technology is yet available on the market.

4.8 Life cycle inputs

This section completes the state-of-play of the current technologies with a description of the resource use in the life cycle phases, these being production and distribution, use (consumables) and end-of-life.

4.8.1 Production phase

Similar as in the first Lot 31 study data from manufacturers shows that product weight (mass, in kg) and reference input power (in kW) are linked.

Equation 14 Mass (kg) calculated on basis of power (kW)[178]

$$\text{Mass} = 85 * \text{Power}^{0.7}$$

where:
Mass = package mass (kg)
Power = power input (kW)

A typical low pressure compressor has a rated power of 16.5 kW and weighs 605 kg, an oil-free compressor would have a rated power of 37.3 kW and weighs 1070 kg.

The material composition by kg product has been kept the same as the low pressure and oil-free compressor in the first Lot 31 study, only the weights have been updated following the renewed data.

Table 72 Material composition of low pressure and oil-free base case product

Material	Low pressure, 16.5 kW mass (kg)	Oil-free, 37.3 kW mass (kg)
high alloy steel 26	18	32
low alloy steel 23	18	32
unalloyed steel 22	266	471
cast iron 24	133	236
aluminium 27	54	96
copper 29	18	32
plastics 11	12	21
insulation material 16	60	107
electronics 98	12	21
others	12	21
assumed powder coating 40	1	2
assumed rubbers 17	1	2

[177] https://www.alphabetenergy.com/

[178] Elaboration by VHK, based on data made available by individual manufacturers, verified with former Lot 31 study data.

assumed Cr-plating 41	0.0012	0.0021
TOTAL	605	1070

No information could be retrieved on primary scrap produced during production (pre-consumer waste).

4.8.2 Distribution phase

Packaging materials

The product is assumed to be assembled on a skid plate (part of the basic package) and may be equipped with rings for heavy lifting. Smaller products may be placed on a wooden pallet and wrapped for protection against elements during transport.

As packaging materials are estimated to be of minor relevance considering the significance of other resource inputs, especially energy consumption and metal resources, the authors have chosen to neglect packaging materials as inputs.

Transport volume

The Ecoreport assigns impacts for distribution based on transport volume. Similar to the first Lot 31 study the transport volume is calculated on the basis of power input.

Equation 15 Product transport volume (m^3) by power (kW)

$$V = 1{,}5 * (Power\text{^}0{,}25)$$

where:
V = transport volume (m^3)
Power = power input (kW)
This results in 3 m^3 for the low pressure compressor and 3.7 m^3 for the oil-free compressor.

Transport distance

As most of the compressor sales will occur in the countries (or regions) with the highest degree of industrialisation, it is assumed that production occurs in mid Germany and use occurs (on average) over a distance of 3 000 km (e.g. Scandinavia, Italy, Spain).

4.8.3 Use phase

Energy

The energy consumption of the average low pressure and oil-free compressor is calculated using the inputs from Task 2 (power) and Task 3 (load factor and operating hours).

Low pressure: 16.5 kW * 0.76 * 3460.4 (h/a) = 43 344 kWh/a

Oil-free: 37.3 kW * 0.84 * 3654.7 (h/a) = 114 775 kWh/a

For the individual flow control range categories the calculation is:

Table 73 Calculation of energy consumption of (basic) compressor package[179]

Category	Power (kW)	Operating hours (h/a)	Load factor (-)	Energy (kWh/a)
LP_WFCR	29.4	3943	0.89	102754

[179] Combination of Pneurop data (low pressure) and VHK elaboration (oil-free mainly).

LP_LFCR	58.4	3902	0.90	204534
LP_ZFCR	8.9	3644	0.78	25340
LP_ZFCRpeak	23.5	2688	0.62	39326
OF_WFCR/air	26.3	3900	0.89	90821
OF_WFCR/water	162.3	3900	0.89	560277
OF_LFCR	185.0	3900	0.89	638528
OF_ZFCR/air	13.7	3595	0.83	40835
OF_ZFCR/water	80.4	3595	0.83	239811
LP_all	16.49	3460	0.76	43344
OF_all	37.33	3654	0.84	114775

Materials

During the use-phase the compressor requires maintenance (changing of air inlet filters, and -if applicable- transmission fluids/oil for gears, etc.) and repair.

It is assumed that some 1% of the original material input is consumed per year.

Real life performance

The efficiencies and energy consumption calculated in the previous paragraphs relates to new compressors. The performance of many compressors however may deteriorate after a certain period.

Certain volumetric compressors designs have their rotors and/or inner surface of the compression chamber coated so that (after an initial "running in" period) the clearance between surfaces is reduced to an absolute minimum. The coating is subject to wear, thermal stress and other factors (worn out bearings causing rotor-to-rotor contact) that cause the coating to deteriorate in a given time, leading to loss of performance / lower efficiency.

The coating materials and the ways to apply them have seen quite some development over the years. The study authors tried to identify studies and other information on the differences in performance between coatings, but found no recent material. A study from 1992 [180] does mention the use of Teflon® and Ryton® as coatings and questioned the durability. However, these polymer based coatings have a relatively short life, requiring refurbishment of the stage every 5 to 10 years [181] and are applied less at higher pressure ratio's (although application in lower pressure ratios apparently still applies).

More modern coatings are metal-containing amorphous carbon coatings with a multi-lamellar structure, applied by a PVD (physical vapour deposition) sputtering machine, giving a much 'tougher' coating[182].

Manufacturers generally do not disclose details (composition and application technique and performance e.g. life in hours) of the coatings they apply and consider this a "trade secret" not to be disclosed to the public. Therefore the effect of coatings on long-term efficiency is not yet properly described.

[180] Glen B. Nordquist et al, Dry screw compressors in process gas applications, Including maintenance considerations, Proceedings of the twenty-first turbomachinery symposium, 1992

[181] http://cascousa.com/compressed-air-101/types-of-compressors/positive-displacement-compressors/

[182] www.oerlikon.com/ecomaXL/files/balzers/oerlikon_HQ040EN_1011_web_locked.pdf

4.8.4 End-of-life phase

The end-of-life phase covers the activities resulting in end-of-waste, these being:

- landfill, pyrolytic incineration without energy recovery;
- recovery (either displacing other material flows, including non-hazardous incineration optimized for energy recovery);
- Re-use or closed-loop recycling.

Task 4 showed that over 80% of the compressor are metals, some of which representing high scrap values (copper, high alloy steel). In Task 3 it is therefore assumed that compressors will end-up in metal scrap dealers because of the economic value of the scrap.

It is assumed that some dismantling takes place to sort the various material fractions and obtain the highest possible scrap values. During this it is assumed that non-metal fractions are separated from metallic fractions and send to separate disposal routes. For plastics it is assumed that at least half of the fractions end up in a waste incineration facility with energy recovery.

Electronics are assumed to be dismantled and send to specialist electronics recyclers as these also represent economic value (presence of precious metals).

Concluding, it is assumed that:

- the metal fraction (ferrous and non-ferrous) is recycled for 99%;
- the plastics fraction is incinerated with heat recovery for 50% and without heat recovery for 50%;
- special fractions like electronics are assumed to be dismantled and are incinerated without heat recovery;
- other inert materials like ceramics (stone or glass wool for insulation) are landfilled.

TASK 5: Environment & economics

5 Environment & economics

5.1 Introduction

In this Task 5 an environmental analysis and life cycle cost analysis (at product and EU level) is made. The analyses are made using the 2014 Ecoreport tool.

5.2 Base-Case Environmental Impact Assessment.

The product specific inputs for the environmental and LCC analysis have been presented in Task 4 (life cycle data for environmental analysis) and Task 2 (economic data for EU LCC). The data relate to the generic low pressure (LP_all) and oil-free (OF_all) product.

5.2.1 Extraction and Production

The tables and figures below present the material inputs for the Ecoreport 2014 calculations.

Table 74 Inputs for extraction and production for LP_all

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable ?
1	high alloy steel 26	18146	3-Ferro	26 -Stainless 18/8 coil	Yes
2	low alloy steel 23	18146	3-Ferro	23 -St tube/profile	Yes
3	unalloyed steel 22	266140	3-Ferro	22 -St sheet galv.	Yes
4	cast iron 24	133070	3-Ferro	24 -Cast iron	Yes
5	aluminium 27	54438	4-Non-ferro	27 -Al sheet/extrusion	Yes
6	copper 29	18146	4-Non-ferro	29 -Cu winding wire	Yes
7	plastics 11	12097	1-BlkPlastics	11 -ABS	Yes
8	insulation material 16	60486	2-TecPlastics	16 -Rigid PUR	No
9	electronics 98	12097	6-Electronics	98 -controller board	No
10	others	12097	7-Misc.	57 -Cardboard	No
11	assumed powder coating 40	1210	5-Coating	40 -powder coating	No
12	assumed rubbers 17	1210	2-TecPlastics	17 -Flex PUR	No
13	assumed Cr-plating 41	1	5-Coating	41 -Cu/Ni/Cr plating	Yes
	TOTAL	607285			

Table 75 Inputs for extraction and production for OF_all

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	high alloy steel 26	32117	3-Ferro	26 -Stainless 18/8 coil	Yes
2	low alloy steel 23	32117	3-Ferro	23 -St tube/profile	Yes
3	unalloyed steel 22	471051	3-Ferro	22 -St sheet galv.	Yes
4	cast iron 24	235525	3-Ferro	24 -Cast iron	Yes
5	aluminium 27	96351	4-Non-ferro	27 -Al sheet/extrusion	Yes
6	copper 29	32117	4-Non-ferro	29 -Cu winding wire	Yes
7	plastics 11	21411	1-BlkPlastics	11 -ABS	Yes
8	insulation material 16	107057	2-TecPlastics	16 -Rigid PUR	No
9	electronics 98	21411	6-Electronics	98 -controller board	No
10	others	21411	7-Misc.	57 -Cardboard	No
11	assumed powder coating 40	2141	5-Coating	40 -powder coating	No
12	assumed rubbers 17	2141	2-TecPlastics	17 -Flex PUR	No
13	assumed Cr-plating 41	2	5-Coating	41 -Cu/Ni/Cr plating	Yes
	TOTAL	1074855			

For both the amount of sheet metal scrap is set at 25%

Figure 60 Material shares for LP_all

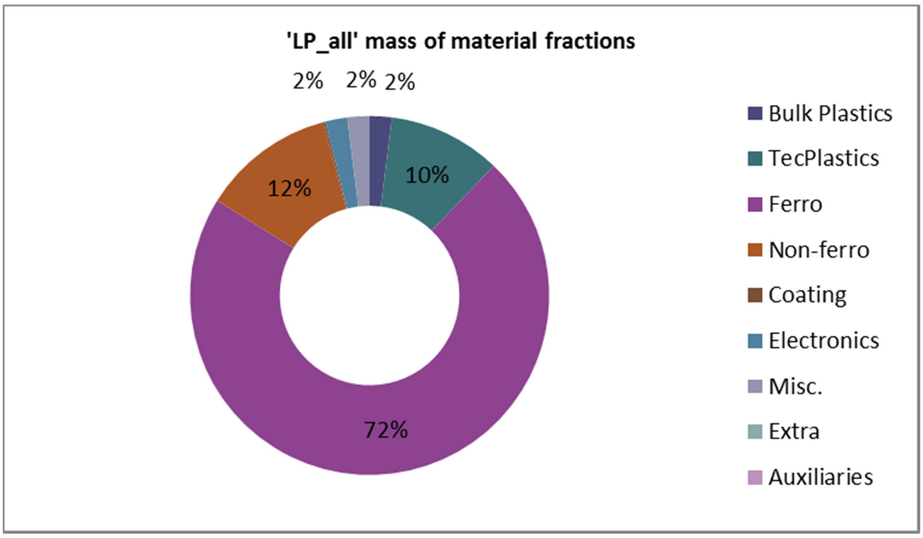
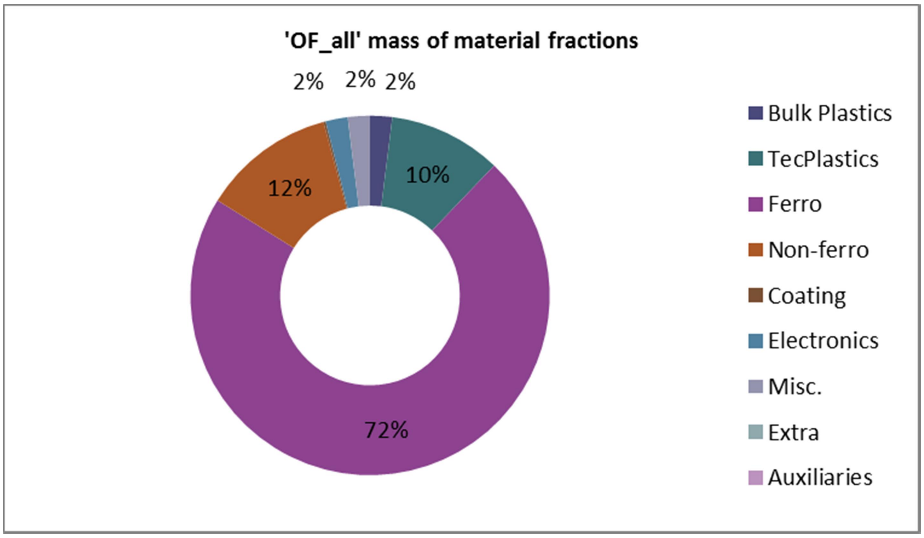


Figure 61 Material shares for OF_all



5.2.2 Distribution phase

The volume of the packaged LP_all compressor is 3 m^3 and for the OF_all compressor 4 m^3. Both are installed products (affects transport impacts).

5.2.3 Use phase

The energy consumption of the LP_all compressor is 43344 kWh/a and for the OF_all compressor 114775 kWh/a. Life is 10.4 and 12.7 respectively.

5.2.4 End-of-life phase

For both products waste scenarios have been set up as shown below. In general it assumes that Ferro metals are recycled with a 95% rate (5% losses to landfill). Non-Ferro (and coating) is recycled at 70%, with 25% incinerated without recovery and 5% losses to landfill. See the table for the other treatment assumptions.

Table 76 Inputs for EOL for both LP_all and OF_all

Pos nr	DISPOSAL & RECYCLING Description				
253	product (stock) life L, in years		(life depends on LP or OF category)		
		current	L years ago	period growth PG in %	CAGR in %/a
254	unit sales in million units/year	0.022	0.023	-1.9%	-0.2%
255	product & aux. mass over service life, in g/unit	613357	613357	0.0%	0.0%
256	total mass sold, in t (1000 kg)	13.79870235	14.06367277	-1.9%	-0.2%

Pos nr	Per fraction (post-consumer)	1 Bulk Plastics	2 TecPlastics	3 Ferro	4 Non-ferro	5 Coating	6 Electronics	7a Misc., excluding refrigant & Hg	7b refrigerant	7c Hg (mercury), in mg/unit	8 Extra	9 Auxiliaries	TOTAL (CARG avg.)
257	current fraction, in % of total mass (or mg/unit Hg)	2.0%	10.2%	71.7%	12.0%	0.2%	2.0%	2.0%	0.0%	0.0	0.0%	0.0%	######
258	fraction x years ago, in % of total mass	2.0%	10.2%	71.7%	12.0%	0.2%	2.0%	2.0%	0.0%	0.0	0.0%	0.0%	######
259	CAGR per fraction r, in %	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	0.0%	0.0%	0.0%	0.0%	
	current product mass in g	*12218*	*62313*	*439857*	*73310*	*1223*	*12218*	*12218*	*0*	*0*	*0*	*0*	*613357*
260	stock-effect, total mass in g/unit	-235	-1197	-8446	-1408	-23	-235	-235	0	0.0	0	0	*-11778*
261	EoL available, total mass ('arisings') in g/unit	12453	63510	448303	74717	1247	12453	12453	0	0.0	0	0	######
262	EoL available, subtotals in g		75963		524267		12453	12453	0	0.0	0	0	######
													AVG
263	EoL mass fraction to re-use, in %						0%			0%		0%	*0.0%*
264	EoL mass fraction to (materials) recycling, in %	0%	0%	95%	70%		50%	0%	0%	0%	25%	25%	*80.7%*
265	EoL mass fraction to (heat) recovery, in %	50%	50%	0%	0%		0%	50%	0%	0%	50%	50%	*7.1%*
266	EoL mass fraction to non-recov. incineration, in %	50%	50%	0%	25%		50%	50%	0%	0%	15%	15%	*8.1%*
267	EoL mass fraction to landfill/missing/fugitive, in %	0%	0%	5%	5%		0%	0%	100%	100%	10%	10%	*4.2%*
268	TOTAL	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*######*
269	EoL recyclability****, (click& select: 'best', '>avg', 'avg' (basecase); '< avg'.; 'worst')	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	avg	*avg*

5.2.5 Impacts over life of a single unit

Table 77 Impacts of a single (generic) LP compressor

	Life Cycle phases -->		PRODUCTION			DISTRI-BUTION	USE	END-OF-LIFE			TOTAL	RBR
	Resources Use and Emissions		Material	Manuf.	**Total**			Disposal	Recycl.	**Stock**		
	Materials	**unit**										
1	Bulk Plastics	g			**12,097**		**121**	6,226	6,226	-235	**0**	
2	TecPlastics	g			**61,696**		**617**	31,755	31,755	-1,197	**0**	
3	Ferro	g			**435,502**		**4,355**	22,415	425,888	-8,446	**0**	
4	Non-ferro	g			**72,584**		**726**	3,736	70,981	-1,408	**0**	
5	Coating	g			**1,211**		**12**	62	1,184	-23	**0**	
6	Electronics	g			**12,097**		**121**	6,226	6,226	-235	**0**	
7	Misc.	g			**12,097**		**121**	6,226	6,226	-235	**0**	
8	Extra	g			**0**		**0**	0	0	0	**0**	
9	Auxiliaries	g			**0**		**0**	0	0	0	**0**	
10	Refrigerant	g			**0**		**0**	0	0	0	**0**	
	Total weight	g			**607,285**		**6,073**	76,647	548,488	-11,778	**0**	
	Other Resources & Waste							debet	see note! credit			
11	Total Energy (GER)	MJ	60,234	9,446	**69,680**	**3,088**	**4,057,601**	1,283	-16,150		**4,115,502**	**0**
12	of which, electricity (in primary MJ)	MJ	24,094	5,492	**29,585**	**9**	**4,057,239**	0	-5,001		**4,081,832**	**0**
13	Water (process)	ltr	10,500	76	**10,577**	**0**	**105**	0	-2,199		**8,483**	**0**
14	Water (cooling)	ltr	22,084	2,394	**24,478**	**0**	**180,532**	0	-3,046		**201,964**	**0**
15	Waste, non-haz./ landfill	g	607,206	41,676	**648,882**	**1,413**	**2,096,779**	6,376	-223,583		**2,529,866**	**0**
16	Waste, hazardous/ incinerated	g	2,568	5	**2,573**	**28**	**64,036**	0	-425		**66,213**	**0**
	Emissions (Air)											
17	Greenhouse Gases in GWP100	kg CO_2 eq.	3,573	536	**4,109**	**200**	**173,215**	5	-1,021		**176,508**	**0**
18	Acidification, emissions	g SO_2 eq.	26,920	2,321	**29,241**	**612**	**766,591**	78	-7,652		**788,870**	**0**
19	Volatile Organic Compounds (VOC)	g	116	8	**124**	**62**	**90,607**	0	-35		**90,759**	**0**
20	Persistent Organic Pollutants (POP)	ng i-Teq	8,554	912	**9,466**	**8**	**9,552**	4	-3,288		**15,741**	**0**
2	Heavy Metals	mg Ni	10,	2,	**12,**	**72**	**41,124**	53	-		**50,6**	**0**

1		eq.	343	117	**460**				3,057		**51**	
22	PAHs	mg Ni eq.	7,265	3	**7,268**	**135**	**9,539**	0	-2,396		**14,546**	**0**
23	Particulate Matter (PM, dust)	g	14,166	355	**14,520**	**10,254**	**16,370**	469	-3,538		**38,075**	**0**
	Emissions (Water)											
24	Heavy Metals	mg Hg/20	8,605	69	**8,674**	**2**	**17,550**	13	-2,470		**23,768**	**0**
25	Eutrophication	g PO4	312	4	**316**	**0**	**769**	40	-65		**1,060**	**0**

Table 78 Impacts of a single (generic) OF compressor

	Life Cycle phases -->		PRODUCTION			DISTRI-BUTION	USE	END-OF-LIFE			TOTAL	RBR
	Resources Use and Emissions		Material	Manuf.	Total			Disposal	Recycl.	Stock		
	Materials	**unit**										
1	Bulk Plastics	g			**21,411**		**214**	12,015	12,015	-2,405	**0**	
2	TecPlastics	g			**109,198**		**1,092**	61,279	61,279	-12,268	**0**	
3	Ferro	g			**770,810**		**7,708**	43,256	821,858	-86,595	**0**	
4	Non-ferro	g			**128,468**		**1,285**	7,209	136,976	-14,433	**0**	
5	Coating	g			**2,143**		**21**	120	2,285	-241	**0**	
6	Electronics	g			**21,411**		**214**	12,015	12,015	-2,405	**0**	
7	Misc.	g			**21,411**		**214**	12,015	12,015	-2,405	**0**	
8	Extra	g			**0**		**0**	0	0	0	**0**	
9	Auxiliaries	g			**0**		**0**	0	0	0	**0**	
10	Refrigerant	g			**0**		**0**	0	0	0	**0**	
	Total weight	g			**1,074,855**		**10,749**	147,911	1,058,445	-120,753	**0**	
					Production	Distribution	**Use**	EOL-disp.	EOL-recycl.			
									see note!			
	Other Resources & Waste							debet	credit			
11	Total Energy (GER)	MJ	106,611	16,718	**123,329**	**4,101**	**13,088,859**	2,476	-31,166		**13,187,599**	**0**
12	of which, electricity (in primary MJ)	MJ	42,645	9,720	**52,364**	**11**	**13,088,220**	0	-9,651		**13,130,944**	**0**
13	Water (process)	ltr	18,585	135	**18,720**	**0**	**186**	0	-4,244		**14,662**	**0**
14	Water (cooling)	ltr	39,087	4,238	43,325	0	582,071	0	-5,879		619,517	0
15	Waste, non-haz./ landfill	g	1,074,71	73,76	**1,148,480**	**1,866**	**6,755,323**	12,304	-431,45		**7,486,514**	**0**

			6	4					9			
16	Waste, hazardous/ incinerated	g	4,546	9	**4,555**	**37**	**206,542**	0	-820		**210,313**	**0**
	Emissions (Air)											
17	Greenhouse Gases in GWP100	kg CO2 eq.	6,324	948	**7,272**	**266**	**558,736**	10	-1,971		**564,313**	**0**
18	Acidification, emissions	g SO2 eq.	47,646	4,108	**51,754**	**811**	**2,472,615**	151	-14,767		**2,510,565**	**0**
19	Volatile Organic Compounds (VOC)	g	206	14	**220**	**83**	**292,296**	0	-67		**292,531**	**0**
20	Persistent Organic Pollutants (POP)	ng i-Teq	15,140	1,614	**16,754**	**11**	**30,690**	7	-6,346		**41,115**	**0**
21	Heavy Metals	mg Ni eq.	18,306	3,747	**22,053**	**95**	**132,515**	102	-5,900		**148,865**	**0**
22	PAHs	mg Ni eq.	12,859	6	**12,864**	**179**	**30,667**	0	-4,624		**39,086**	**0**
23	Particulate Matter (PM, dust)	g	25,072	628	**25,700**	**13,673**	**52,602**	904	-6,827		**86,052**	**0**
	Emissions (Water)											
24	Heavy Metals	mg Hg/20	15,231	121	**15,352**	**3**	**56,490**	25	-4,767		**67,102**	**0**
25	Eutrophication	g PO4	552	7	**559**	**0**	**2,478**	77	-125		**2,988**	**0**

The figures below show the harmonised impacts of the impact categories per product life (total over life is 100%).

Figure 62 LP_all impacts per phase

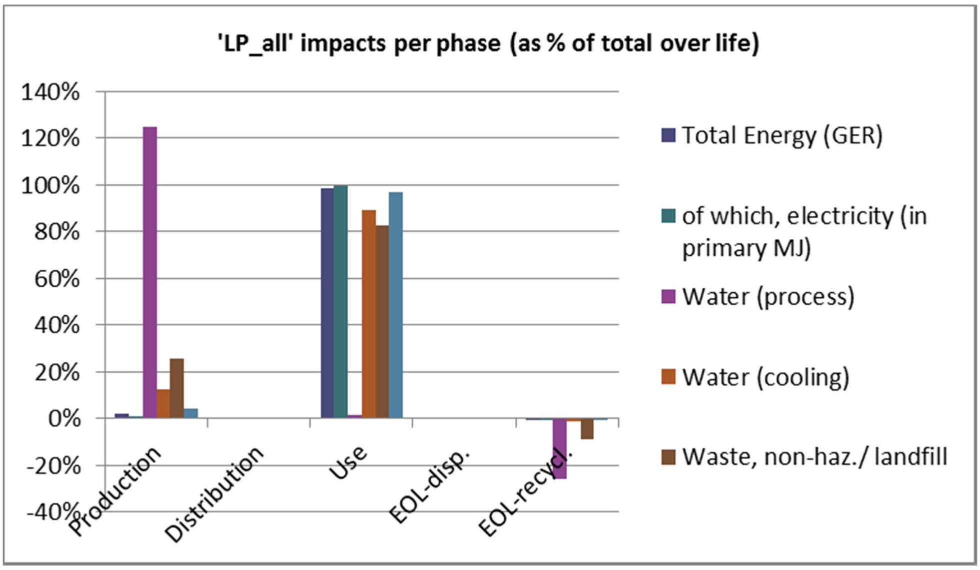
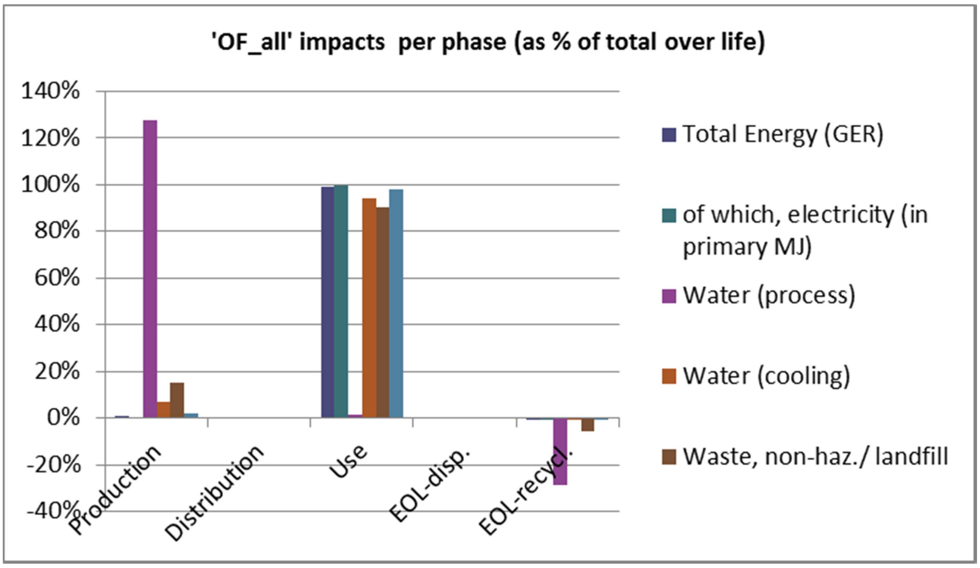


Figure 63 OF_all impacts per phase



5.3 EU Total Life Cycle Costs

This section shows the life cycle costs of the product, and for the EU 28 society, using the Ecoreport template. External damages have been added, also using the Ecoreport 2014 template and default values.

Table 79 Life cycle costs (including damages) of LP_all

	Generic Low Pressure Compressor (LP_all) Item		LCC new product			total annual consumer expenditure in EU28	
D	Product price		27,500	€		**619**	mln.€
E	Installation/ acquisition costs (if any)		965	€		**22**	mln.€
F	Fuel (gas, oil, wood)		0	€		**0**	mln.€
F	Electricity		49,586	€		**1,056**	mln.€
G	Water		0	€		**0**	mln.€
H	Aux. 1: None		0	€		**0**	mln.€
I	Aux. 2 :None		0	€		**0**	mln.€
J	Aux. 3: None		0	€		**0**	mln.€
K	Repair & maintenance costs		7,260	€		**155**	mln.€
L	**External damages total, of which**		10,132			**217**	mln.€
	- production PPext	709			**16**		
	- lifetime operating expense N*OEext	9,288			**198**		
	- end-of-life OELext	135			**3**		
	Total		**95,442**	€		**2,068**	mln.€

Table 80 Life cycle costs (including damages) of OF_all

	Generic Oil-free Compressor (OF_all) Item		LCC new product			total annual consumer expenditure in EU28	
D	Product price		58,114	€		**538**	mln.€
E	Installation/ acquisition costs (if any)		1,173	€		**11**	mln.€
F	Fuel (gas, oil, wood)		0	€		**0**	mln.€
F	Electricity		159,962	€		**1,518**	mln.€
G	Water		0	€		**0**	mln.€
H	Aux. 1: None		0	€		**0**	mln.€
I	Aux. 2 :None		0	€		**0**	mln.€
J	Aux. 3: None		0	€		**0**	mln.€
K	Repair & maintenance costs		20,784	€		**197**	mln.€
L	**External damages total, of which**		31,418			**298**	mln.€
	- production PPext	1,182			**11**		
	- lifetime operating expense N*OEext	29,955			**284**		
	- end-of-life OELext	281			**3**		
	Total		**271,451**	€		**2,562**	mln.€

5.4 EU Total, impacts per year

The combined impacts of the stock of products (in 2015) is compared with the average EU28 impacts (data refer to 2011, but will not have changed drastically).

Table 81 EU total impacts (harmonised) for LP_all

Table . Summary Environmental Impacts EU-Stock 2015,					
Main life cycle indicators	value	unit	%	EU totals	Reference
Materials					
Plastics	0.002	Mt	0.003%	48	Ref: Plastics Europe (demand by EU converters) [1]
Ferrous metals	0.010	Mt	0.005%	206	Ref: Iron & Steel Statistics Bureau [1]
Non-ferrous metals	0.002	Mt	0.008%	20	Ref: www.eaa.net et al. (Al 12,5+Cu 4,7 + Zn 0,8 + Pb 0,8 + Ni 0,3)
Other resources & waste					
Total Energy (GER)	88	PJ	0.116%	75,697	Eurostat, Gross Inland Consumption EU-27, 2007, in Net Calorific Value
of which, electricity	10	TWh	0.346%	2,800	Final end-use. Ref: Eurostat
Water (process)*	0	mln.m3	0.000%	247,000	Ref: http://ec.europa.eu/environment/water/quantity/pdf/exec_summary.pdf [1]
Waste, non-haz./ landfill*	0.06	Mt	0.002%	2,947	Ref: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php?title=File:Generation_of_waste,_total_arising_and_by_selected_economic_activities.
Waste, hazardous/ incinerated*	0.00	kton	0.002%	89	
Emissions (Air)					
Greenhouse Gases in GWP100	4	mt CO2eq.	0.07%	5,054	Ref: EEA3 (CO2 4187 + CH4 416 + N2O 374 + HFCs 63 + PFCs 4 + SF6 10)
Acidifying agents (AP)	17	kt SO2eq.	0.08%	22,432	Ref: EEA1 (Nox 11 151 + Sox 7 339 + NH3 3 876)

Volatile Org. Compounds (VOC)	2	kt	0.02%	8,951	Ref: EEA1
Persistent Org. Pollutants (POP)	0	g i-Teq.	0.02%	2,212	Ref: EEA1 (dioxins and furans only)
Heavy Metals (HM)	1	ton Ni eq.	0.02%	5,903	Ref: EEA1 (Cd 118 + Hg 89 + Pb 2157 t); EEA2 (As 337 + Ni 2843 t); CML (Cr 517 + Cu 589 + Zn 6510 t)
PAHs	0	ton Ni eq.	0.03%	1,369	Ref: EEA1
Particulate Matter (PM, dust)	1	kt	0.03%	3,522	Ref: EEA1 (1400 kt PM2,5 + 2122 kt PM10)
Emissions (Water)					
Heavy Metals (HM)	1	ton Hg/20	0.00%	12,853	Ref: CML (As 17+Cd 21,3 + Cr 271 + Cu 1690 + Pb 2260 + Hg 14,3 + Ni 551 t + Zn 11200 t)
Eutrophication (EP)	0	kt PO4	0.00%	900	Ref: EEA2 (Baltic 861 N/5,4 P + North Sea 761 N/14,4 P + Danube/Black Sea 270 N/ 14,2 P)

Table 82 EU total impacts (harmonised) for OF_all

Table . Summary Environmental Impacts EU-Stock 2015,					
Main life cycle indicators	value	unit	%	EU totals	Reference
Materials					
Plastics	0.001	Mt	0.003%	48	Ref: Plastics Europe (demand by EU converters) [1]
Ferrous metals	0.007	Mt	0.003%	206	Ref: Iron & Steel Statistics Bureau [1]
Non-ferrous metals	0.001	Mt	0.006%	20	Ref: www.eaa.net et al. (Al 12,5+Cu 4,7 + Zn 0,8 + Pb 0,8 + Ni 0,3)
Other resources & waste					
Total Energy (GER)	125	PJ	0.166%	75,697	Eurostat, Gross Inland Consumption EU-27, 2007, in Net Calorific Value
of which, electricity	14	TWh	0.495%	2,800	Final end-use. Ref: Eurostat
Water (process)*	0	mln.m3	0.000%	247,000	Ref: http://ec.europa.eu/environment/water/quantity/pdf/exec_summary.pdf [1]
Waste, non-haz./ landfill*	0.07	Mt	0.003%	2,947	Ref: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php?title=File:Generation_of_waste,_total_arising_and_by_selected_economic_activities.
Waste, hazardous/ incinerated*	0.00	kton	0.002%	89	
Emissions (Air)					
Greenhouse Gases in GWP100	5	mt CO2eq.	0.11%	5,054	Ref: EEA3 (CO2 4187 + CH4 416 + N2O 374 + HFCs 63 + PFCs 4 + SF6 10)
Acidifying agents (AP)	24	kt SO2eq.	0.11%	22,432	Ref: EEA1 (Nox 11 151 + Sox 7 339 + NH3 3 876)
Volatile Org. Compounds (VOC)	3	kt	0.03%	8,951	Ref: EEA1
Persistent Org. Pollutants (POP)	0	g i-Teq.	0.02%	2,212	Ref: EEA1 (dioxins and furans only)
Heavy Metals (HM)	1	ton Ni eq.	0.02%	5,903	Ref: EEA1 (Cd 118 + Hg 89 + Pb 2157 t); EEA2 (As 337 + Ni 2843 t); CML (Cr 517 + Cu 589 + Zn 6510 t)
PAHs	0	ton Ni eq.	0.03%	1,369	Ref: EEA1
Particulate Matter (PM, dust)	1	kt	0.02%	3,522	Ref: EEA1 (1400 kt PM2,5 + 2122 kt PM10)
Emissions (Water)					
Heavy Metals (HM)	1	ton Hg/20	0.01%	12,853	Ref: CML (As 17+Cd 21,3 + Cr 271 + Cu 1690 + Pb 2260 + Hg 14,3 + Ni 551 t + Zn 11200 t)
Eutrophication (EP)	0	kt PO4	0.00%	900	Ref: EEA2 (Baltic 861 N/5,4 P + North Sea 761 N/14,4 P + Danube/Black Sea 270 N/ 14,2 P)

The tables on EU impacts shows that LP is responsible for 0.35% and OF for 0.5% of EU total electricity consumption, combined almost 1% of the EU total.

The first Lot 31 study on 'Standard air' concluded that their consumption was close to 58 TWh, which is some 2% of the EU total.

TASK 6: Design options

6 Design options

6.1 Introduction

In this Task 6 the design option(s) for reducing the impact of the most significant environmental parameters are identified.

Options are assessed on the basis of their Life Cycle Cost (for the consumer), their environmental costs and benefits. The solution with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT) is identified, as these may be used as policy targets for the short and medium term.

6.2 Options for energy saving

From the Task 5 analysis the main environmental parameter to be addressed is identified as: Energy consumption during the use-phase.

Options to reduce this energy consumption (see also Task 4) are:

1. Improving package energy efficiency;
2. Applying VSD's in fixed speed equipment;
3. Applying heat recovery.

6.2.1 Improving package energy efficiency

Design options

At the strict product level (the bare compressor or 'air end') one can imagine improvement of geometry of moving and stationary components and the use of multiple stages instead of a single stage.

- Applying more stages with intercooling the package becomes (all else equal) more efficient is the change of state is getting closer to isothermal compression. Generally speaking, the benefits of multi-staging depend on the application, especially pressure ratio and intercooling possibilities. As every additional stage creates additional losses these have to be overcompensated by the thermodynamic advantage of intercooling.
- As regards multi-staging, to corroborate this, DOE analysed pairs of single- and two-stage (lubricated) rotary screw compressors. Pairs were matched by manufacturer, full-load operating pressure, similar capacity, motor horsepower, and fan horsepower. The set of pairs showed that two-stage units improved specific power 11-percent over similar single-stage units[183].

There are some constraints to implementing improvements:

- Manufacturers can develop air ends with (a) specific operating condition(s) in mind, but developing an air end is expensive as it requires tooling of manufacturing equipment. Furthermore, parts are usually kept for some 15 years after end of production of the related package. Therefore manufacturers tend to limit the number of air ends to achieve economies of scale.
- In general the operating envelope of a technology (min/max flow or pressure) can be expanded by changing the design (geometry), but this exercise has its limits. For instance: by downsizing an air end, the volume flow is reduced by the cube of the dimensional change. The internal leakage is however reduced by only the square of the dimensional change. The relative losses will thus increase. Other factors also contribute to reduced efficiency in case of downsizing.
- These other factors are, besides increasing (relative) importance of leakage, increased frictional flow losses, machining tolerances not scaling down with size, lower efficiency of

[183] According Pneurop this is a very special case, comparing a single and 2-stage lubricated machine.

smaller electrical motors or drive systems, mechanical losses not scaling down with size or input power, practical limitations to increase rotational speed in proportion to size reduction etc.

At the extended product level (the air end, plus motor, transmission and motor drive and other parts of the basic package) improvements may relate to: reducing the internal pressure drop (wider pipes, reduced bends, improved condensate traps), improved efficiency of the electric motor, improved efficiency of the transmission (direct drive instead of belts or gears), reduced electric losses of the motor drivers and/or other electronics in the package, reduced losses of other motors within the package (fans for cooling air), better control algorithms (within package boundaries), etc.

- Improvements beyond the package boundaries (such as improving the technique for removing moisture from the compressed air) are beyond the boundaries of this assessment.

Experts, and also the DOE study, confirmed that manufacturers assess these options in combination, not in isolation, to improve overall package efficiency.

Relation D-value and package efficiency

Similar to the first Lot 31 study on standard air compressor packages, the present study focuses on the overall improvement of the total package. The improvement of the package is expressed using the "D-value", which is the proportional change in the loss of the compressor. The "loss" is the difference between the (average) isentropic efficiency of the compressor package (D=0 by default) and an 'ideal' isentropic compression having an efficiency of 100% (D=100). The calculation below shows the principle.

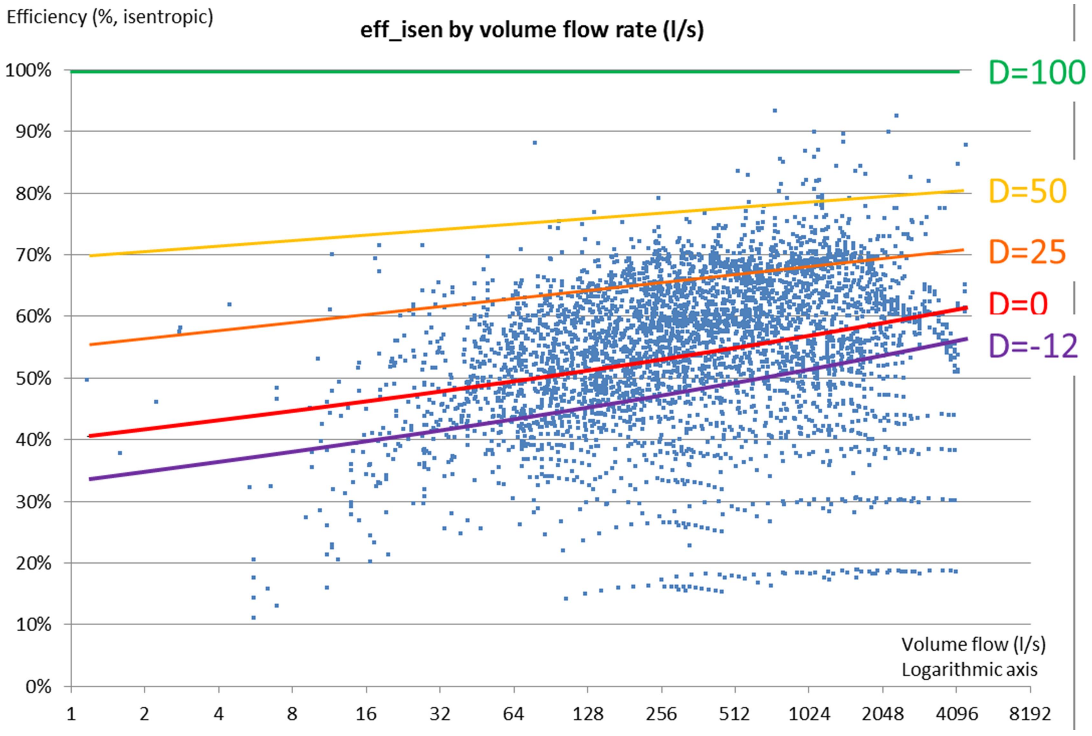
Table 83 Example of calculating efficiencies when knowing the average and a D-value

D-value	Calculation (if applicable)	Efficiency
D=100	(no calculation, D=100 means it is the theoretical maximum isentropic efficiency assuming an ideal gas and ideal compression process – only used for reference)	100% by default
D=0	(no calculation, D=0 means it is the average efficiency for a group of products)	For this example: 60% (value applies to specific operating conditions)
D= 15	Now, D=15 means a change in efficiency of +15% between D=0 (60%) and D=100 (100%). Calculation: 15%*(100%-60%) = 6%	If D=15, efficiency is (60%+6% =) 66%
D= -15	Similarly, D= -15 means a change in efficiency of (minus) 15% between D=0 (60%) and D=100 (100%). Calculation: -15%*(100%-60%) = -6%	If D= -15, efficiency is (60%-6% =) 54%
Therefore the efficiency is expressed as the change between an average and "ideal" efficiency. Only if the average efficiency is known, for a certain group of products at comparable operating conditions, an absolute efficiency value can be assigned to a D-value.		

A single D-value can therefore represent the efficiency of a group of products, depending how the average of the group is represented (curve, single value, etc.).

When presented using a graph, it is easy to see that the D-value shifts the "average" D=0 curve up and down, proportional to the distance to the 100% efficiency (D=100) curve.

Figure 64 Shifting an efficiency curve up and down by defining a D-value



6.2.2 Life cycle costs of improvement of package energy efficiency

The life cycle cost analysis is performed at the level of combined options as no breakdown in individual design options is available.

The relation between package efficiency and purchase costs (and package size, expressed as average motor power) has been as described in Task 2 (see Direct costs, Purchase prices).

Life cycle costs for design options related to improving package energy efficiency show that energy costs dominate the life cycle cost and all efforts, up to improving the package to efficiency level comparable to D=0 (meaning the equipment has a minimum efficiency equal to the average efficiency) result in lower life cycle costs.

The assessment is based on comparing options with a package efficiency defined by D=0 (is average product, or "base case"), 5, 10, 15 and 20 (no negative values for D have been assessed as it makes no sense to calculate the benefits of a worse than average product).

Table 84 Efficiency of options assessed

Package efficiency	D-value				
	0 (=BC)	5	10	15	20
LP_WFCR	56.0%	58.2%	60.4%	62.6%	64.8%
LP_LFCR	67.7%	69.3%	70.9%	72.5%	74.1%
LP_ZFCR	38.2%	41.3%	44.4%	47.5%	50.6%
LP_ZFCRpeak	51.7%	54.1%	56.6%	59.0%	61.4%
OF_WFCR/air	55.3%	57.5%	59.8%	62.0%	64.2%
OF_WFCR/water	66.4%	68.1%	69.7%	71.4%	73.1%

OF_LFCR	64.3%	66.1%	67.9%	69.7%	71.4%
OF_ZFCR/air	52.6%	54.9%	57.3%	59.7%	62.1%
OF_ZFCR/water	69.3%	70.8%	72.4%	73.9%	75.4%

The following costs have been calculated, using inputs from this Task and/or preceding Tasks.

Table 85 Purchase price (EUR/life) of options assessed

Purchase price	Power (kW)	D=0	=5	=10	=15	=20
LP_WFCR	29.4	15634	16127	16615	17099	17577
LP_LFCR	58.4	29409	29967	30520	31071	31618
LP_ZFCR	8.9	5011	5344	5671	5991	6307
LP_ZFCRpeak	23.5	12545	13018	13484	13945	14401
OF_WFCR/air	26.3	14320	14785	15246	15701	16153
OF_WFCR/water	162.3	59777	60980	62174	63360	64538
OF_LFCR	185.0	63985	65398	66800	68192	69574
OF_ZFCR/air	13.7	8739	9056	9370	9681	9988
OF_ZFCR/water	80.4	37559	38219	38874	39525	40173

Table 86 Installation costs (EUR/life) of options assessed

Installation costs	Power (kW)	D=0	=5	=10	=15	=20
LP_WFCR	29.4	1094	1094	1094	1094	1094
LP_LFCR	58.4	1384	1384	1384	1384	1384
LP_ZFCR	8.9	889	889	889	889	889
LP_ZFCRpeak	23.5	1035	1035	1035	1035	1035
OF_WFCR/air	26.3	1063	1063	1063	1063	1063
OF_WFCR/water	162.3	2423	2423	2423	2423	2423
OF_LFCR	185.0	2650	2650	2650	2650	2650
OF_ZFCR/air	13.7	937	937	937	937	937
OF_ZFCR/water	80.4	1604	1604	1604	1604	1604

Energy costs are assessed assuming an escalation rate of 4% and a discount rate of 4%. The PWF (present worth factor) is 1.0.

Table 87 Energy costs (EUR/life) of options assessed

Energy costs (EUR/life,corr.)	Life (y)	D=0	=5	=10	=15	=20
LP_WFCR	12.1	124,913	120,189	115,808	111,736	107,941
LP_LFCR	12.2	259,464	253,408	247,628	242,106	236,825
LP_ZFCR	8.4	23,423	21,673	20,166	18,855	17,705
LP_ZFCRpeak	13.2	53,190	50,819	48,650	46,659	44,824
OF_WFCR/air	11.7	126,776	121,848	117,288	113,057	109,121

OF_WFCR/water	16.2	1,112,707	1,085,217	1,059,052	1,034,119	1,010,333
OF_LFCR	16.6	1,337,210	1,301,106	1,266,899	1,234,446	1,203,613
OF_ZFCR/air	10.4	53,102	50,809	48,707	46,771	44,983
OF_ZFCR/water	14.3	427,166	417,904	409,034	400,533	392,378

Maintenance costs are assessed with a discount rate of 4%, the PWF ranges from 0.55 (for the long life products) to 0.73 (for the shorter lived products).

Table 88 Maintenance/repair/filter costs (EUR/life) of options assessed

Maintenance, incl. filter (EUR/life,corr.)	Annual costs (as % of purchase costs)	D=0	=5	=10	=15	=20
LP_WFCR	7%	8,548	8,800	9,049	9,296	9,540
LP_LFCR	5%	12,309	12,526	12,740	12,953	13,165
LP_ZFCR	6%	2,003	2,119	2,232	2,343	2,453
LP_ZFCRpeak	8%	8,134	8,420	8,703	8,983	9,260
OF_WFCR/air	9%	10,400	10,719	11,036	11,349	11,659
OF_WFCR/water	9%	49,915	50,868	51,815	52,755	53,689
OF_LFCR	5%	32,721	33,380	34,034	34,683	35,328
OF_ZFCR/air	9%	6,300	6,515	6,728	6,938	7,147
OF_ZFCR/water	9%	31,150	31,673	32,193	32,711	33,225

Refurbishment costs have also been assessed.

Table 89 Refurbishment costs (EUR/life) of options assessed

Refurbishment (EUR/life,corr.)	Share of PP	D=0	=5	=10	=15	=20
LP_WFCR	75%	11725	12095	12461	12824	13183
LP_LFCR	75%	22057	22475	22890	23303	23713
LP_ZFCR	75%	3758	4008	4253	4494	4730
LP_ZFCRpeak	75%	9409	9763	10113	10459	10801
OF_WFCR/air	100%	14320	14785	15246	15701	16153
OF_WFCR/water	100%	59777	60980	62174	63360	64538
OF_LFCR	100%	63985	65398	66800	68192	69574
OF_ZFCR/air	100%	8739	9056	9370	9681	9988
OF_ZFCR/water	100%	37559	38219	38874	39525	40173

As regards disposal costs, the scrap represents an economic value (negative costs) as shown below. This disposal value does not include transport, separation and treatment costs as the Task 3 analysis showed these are very susceptible to factors beyond the sphere of influence of the manufacturer (decisive are labour costs and transport distance).

Table 90 Disposal value (EUR/life) of options assessed

Disposal value (EUR/life)	Power (kW)	D=0	=5	=10	=15	=20
LP_WFCR	29.4	170	170	170	170	170
LP_LFCR	58.4	315	315	315	315	315
LP_ZFCR	8.9	58	58	58	58	58
LP_ZFCRpeak	23.5	139	139	139	139	139
OF_WFCR/air	26.3	154	154	154	154	154
OF_WFCR/water	162.3	790	790	790	790	790
OF_LFCR	185.0	889	889	889	889	889
OF_ZFCR/air	13.7	85	85	85	85	85
OF_ZFCR/water	80.4	420	420	420	420	420

The life cycle costs without refurbishment costs and disposal revenue show that energy costs are dominant.

Table 91 Life cycle costs (EUR/life) of options assessed, excluding refurbishment and disposal

Costs excl. refurbish+disposal (EUR/life)	D=0	=5	=10	=15	=20
LP_WFCR	€150,190	€146,210	€142,567	€139,225	€136,153
LP_LFCR	€302,567	€297,284	€292,273	€287,514	€282,992
LP_ZFCR	€31,326	€30,025	€28,958	€28,079	€27,353
LP_ZFCRpeak	€74,904	€73,292	€71,873	€70,622	€69,520
OF_WFCR/air	€152,559	€148,415	€144,632	€141,171	€137,996
OF_WFCR/water	€1,224,823	€1,199,488	€1,175,464	€1,152,657	€1,130,984
OF_LFCR	€1,436,566	€1,402,533	€1,370,383	€1,339,971	€1,311,165
OF_ZFCR/air	€69,077	€67,318	€65,742	€64,327	€63,055
OF_ZFCR/water	€497,479	€489,399	€481,705	€474,372	€467,379

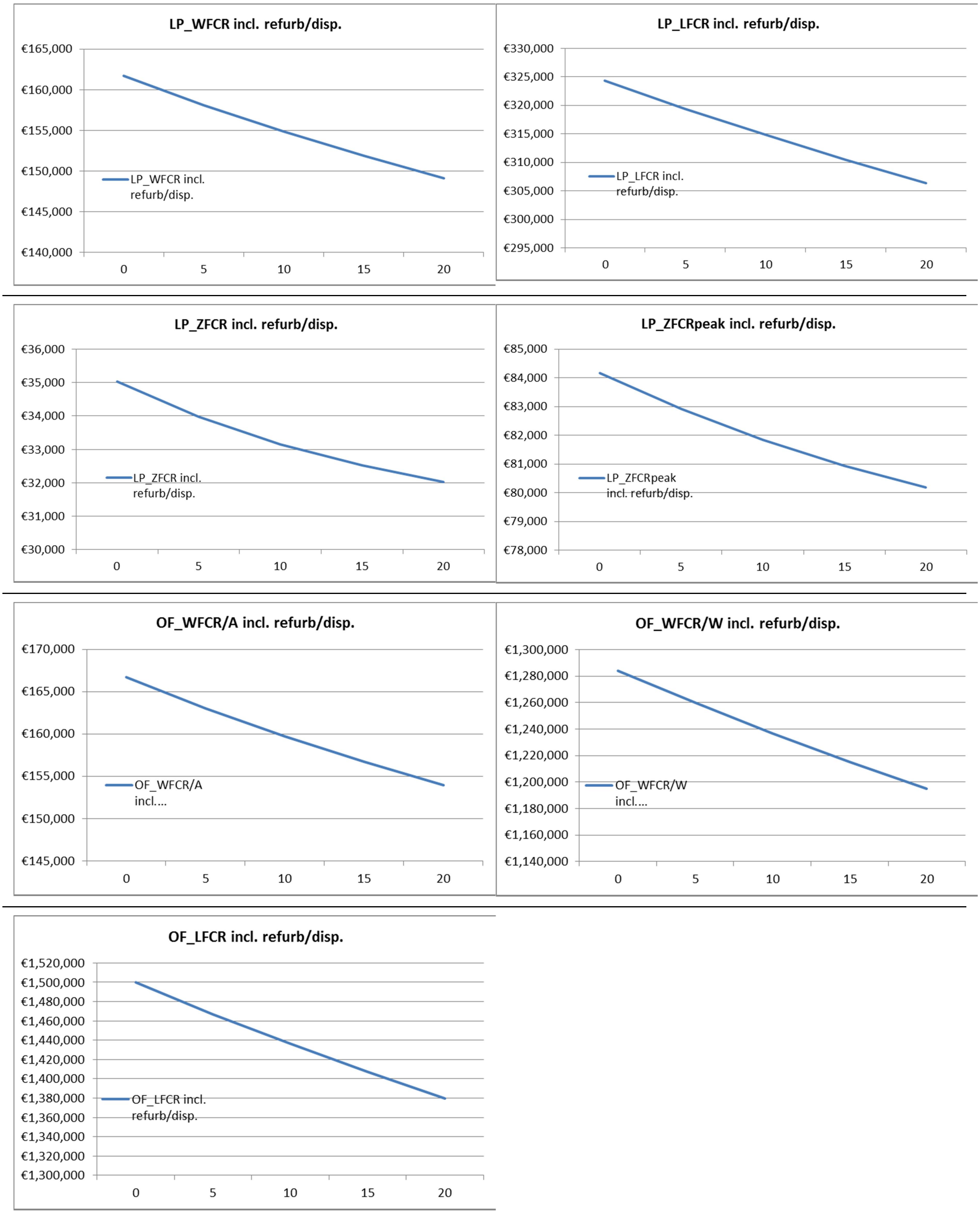
If the refurbishment costs and disposal revenue are added to the life cycle costs the overall picture does not change. Energy costs remain dominant.

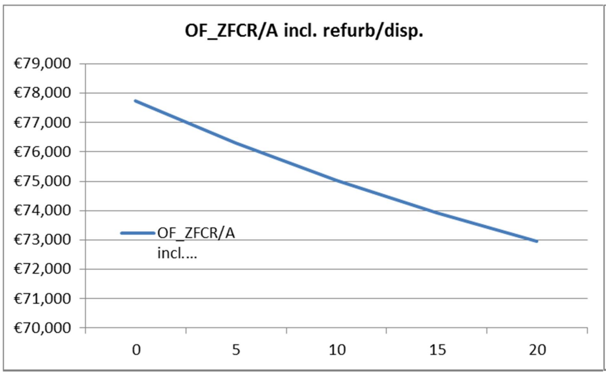
Table 92 Life cycle costs (EUR/life) of options assessed, including refurbishment and disposal

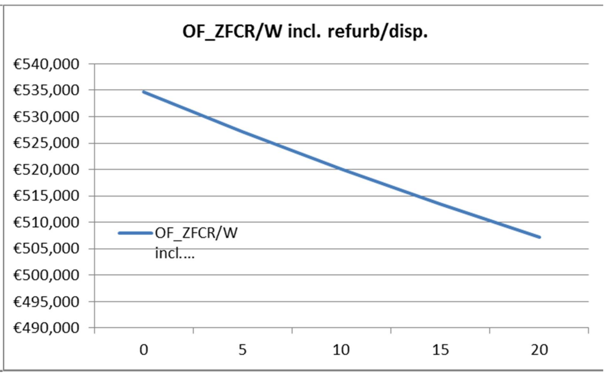
Costs incl. refurbish+disposal (EUR/life)	D=0	=5	=10	=15	=20
LP_WFCR	€161,745	€158,135	€154,859	€151,879	€149,166
LP_LFCR	€324,309	€319,444	€314,848	€310,503	€306,390
LP_ZFCR	€35,026	€33,975	€33,153	€32,515	€32,025
LP_ZFCRpeak	€84,175	€82,916	€81,847	€80,942	€80,183
OF_WFCR/air	€166,725	€163,047	€159,724	€156,718	€153,995
OF_WFCR/water	€1,283,810	€1,259,677	€1,236,847	€1,215,227	€1,194,732
OF_LFCR	€1,499,663	€1,467,042	€1,436,294	€1,407,274	€1,379,850

OF_ZFCR/air	€77,730	€76,289	€75,027	€73,923	€72,958
OF_ZFCR/water	€534,618	€527,197	€520,159	€513,478	€507,132

Figure 65 Life cycle costs curves for LP and OF, incl. refurbishment/disposal (horizontal: D-value, vertical: costs (EUR/life))







The LCC curves show the dominance of the energy costs, causing the curves to slope down with ever increasing efficiency. This means that there is no "least" life cycle cost point within the range of improvement assessed.

This does not mean that these compressors can be improved limitless, for several reasons:

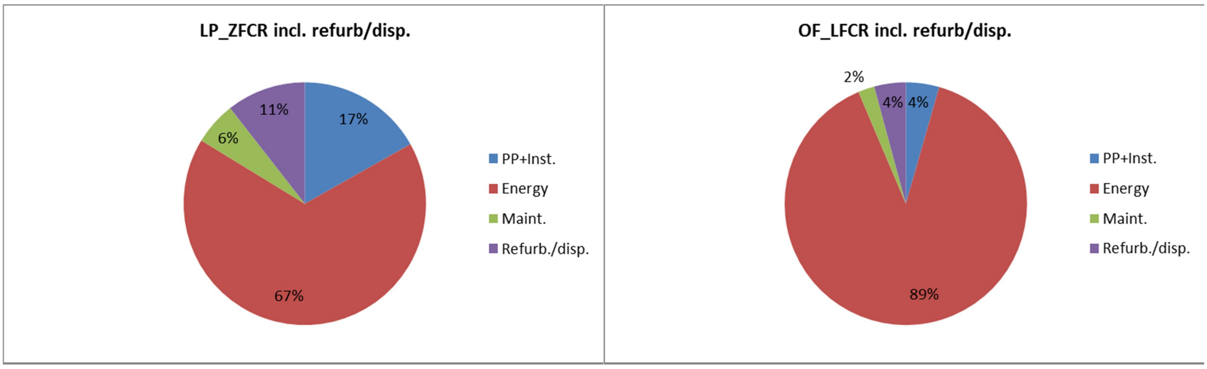
- The assessment of compressor package prices was based on a limited dataset. Describing the price elasticity for efficiency through an equation reduced detail further and removed outliers. It may be that for certain operating conditions and technologies prices are higher (or lower) than described in this section.
- Setting minimum efficiency targets will remove a certain share of products from the market. Harsh targets will affect businesses investment, which is not taken into account in this LCC level (but is taken into account in Task 7, policy options).

The share of the various elements that make up the life cycle costs is shown in the table below. Values relate to both LCC excluding refurbishment/disposal and including refurbishment/disposal.

Table 93 Share of LCC costs by life cycle cost element

Excluding refurb./disp.				**Including refurb./disp.**				
Costs (EUR/life)	**PP+Inst.**	**Energy**	**Maint.**	**Costs (EUR/life)**	**PP+Inst.**	**Energy**	**Maint.**	**Refurb. /disp.**
LP_WFCR	11%	83%	6%	LP_WFCR	10%	77%	5%	7%
LP_LFCR	10%	86%	4%	LP_LFCR	9%	80%	4%	7%
LP_ZFCR	19%	75%	6%	LP_ZFCR	17%	67%	6%	11%
LP_ZFCRpeak	18%	71%	11%	LP_ZFCRpeak	16%	63%	10%	11%
OF_WFCR/air	10%	83%	7%	OF_WFCR/air	9%	76%	6%	8%
OF_WFCR/water	5%	91%	4%	OF_WFCR/water	5%	87%	4%	5%
OF_LFCR	5%	93%	2%	OF_LFCR	4%	89%	2%	4%
OF_ZFCR/air	14%	77%	9%	OF_ZFCR/air	12%	68%	8%	11%
OF_ZFCR/water	8%	86%	6%	OF_ZFCR/water	7%	80%	6%	7%

Figure 66 Costs per TCO-element for LP and OF, example ZFCR



LP_ZFCR power = 8.9 kW OF_ZFCR power = 185 kW

The simple payback rate of the design options is calculated as:

SPPab= (PPref-PPopt)/((OEopt-OEref)/life)

Table 94 Simple payback rate (years)

simple payback in years	0	5	10	15	20
LP_WFCR	(ref.)	1.26	1.30	1.34	1.38
LP_LFCR		1.13	1.15	1.17	1.19
LP_ZFCR		1.60	1.70	1.80	1.90
LP_ZFCRpeak		2.64	2.74	2.84	2.94
OF_WFCR/A		1.23	1.27	1.32	1.36
OF_WFCR/W		0.79	0.81	0.83	0.84
OF_LFCR		0.73	0.74	0.76	0.78
OF_ZFCR/A		1.61	1.67	1.73	1.79
OF_ZFCR/W		1.14	1.16	1.18	1.20

6.3 Long-term targets (BNAT) and systems analysis

On the longer term it is foreseeable that the simple improvement of package efficiency will slow down, as limits in (for instance) machining tolerances and design are reached.

Other options for achieving energy savings, as identified in Task 4, relate to:

applying VSD's to fixed speed equipment;

applying heat recovery.

These two 'options' have been assessed, although the depth of analysis is less than that of the conventional design options.

6.3.1 Applying VSD's in fixed speed categories

The section 4.5 on part load operation shows that, in certain applications, a compressor with a VSD could operate more efficiently than compressors using other forms of flow control.

Applying a VSD as flow control method is however not an option that applies universally, to all fixed speed equipment. In certain combinations of technology and air demand (such as a large baseload compressor) the addition of a VSD could lead to an energy loss, as its potential for saving would remain untapped. In other installations, retrofitting a machine with a VSD may not work as the machine may be ill-equipped to handle variable flows: The air-end may be sized in a way that reducing the flow would reduce efficiency noticeably. Or the existing motor may not be designed to handle the conversion from fixed-speed to variable speed. Proper cooling of the motor during low-speed operations also needs to be considered.

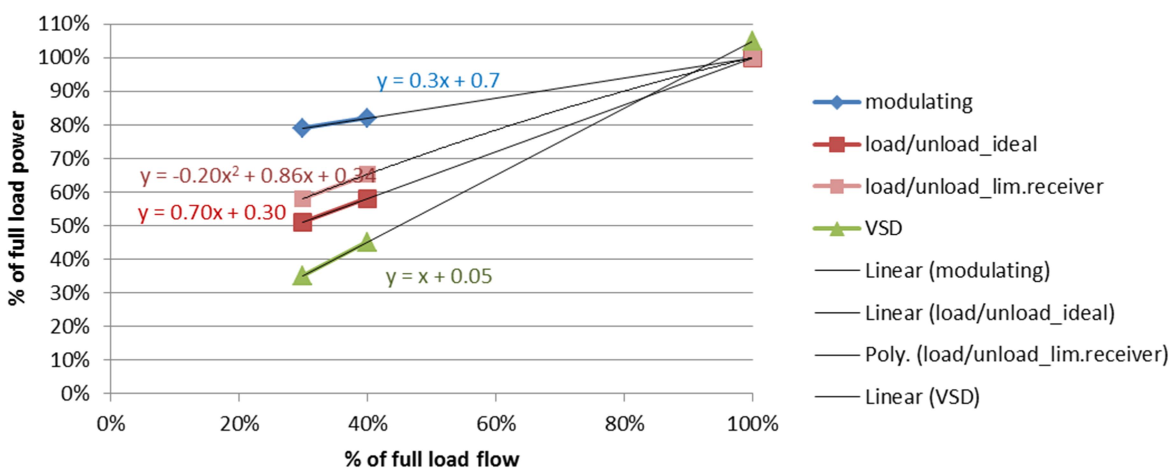
Therefore it is considered standard practice for manufacturers when specifying equipment to customers to match machines of different sizes and designs (e.g. air-end technology or flow control capability) with air flow demands in an optimal way. This means selecting the "right" machine and the "right" control method. This also means that in the case of retrofitting existing machinery with a VSD, this should be done with "the blessing" of the original equipment manufacturer.

Having said this, this option explores the potential benefits (and indicative costs) of an increase in VSD driven applications, as it is assumed that sales, especially in the low power ZFCR categories, are still very much first cost driven and the uptake of VSD could be improved.

Suboptimal matching of compressor and air demand may be the case where the customer is not (sufficiently) aware of fluctuations in air demand, or where the customer wilfully selects a (fixed speed) compressor with a certain overcapacity as he/she foresees a growing need for compressed air in the near future. In many cases capital equipment is oversized as customers apply a 'fudge factor' so that the risks of acquiring undersized equipment is reduced[184]. Customers may also experience a seasonal shift in compressed air needs, which means that part of the year the equipment is oversized.

The power consumption as % of full flow power of above described control methods are depicted below, with load/unload described for the 'ideal' situation (with receiver capacity and pressure differential matched to a load/unload control algorithm) and a 'limited receiver' situation, whereby the receiver capacity is too small (leading to frequent unloading) or too large (leading to unnecessary long load times). Admittedly the figure is a drastic simplification of real compressor behaviour.

Figure 67 Power as % full load power for various flow control methods[185]



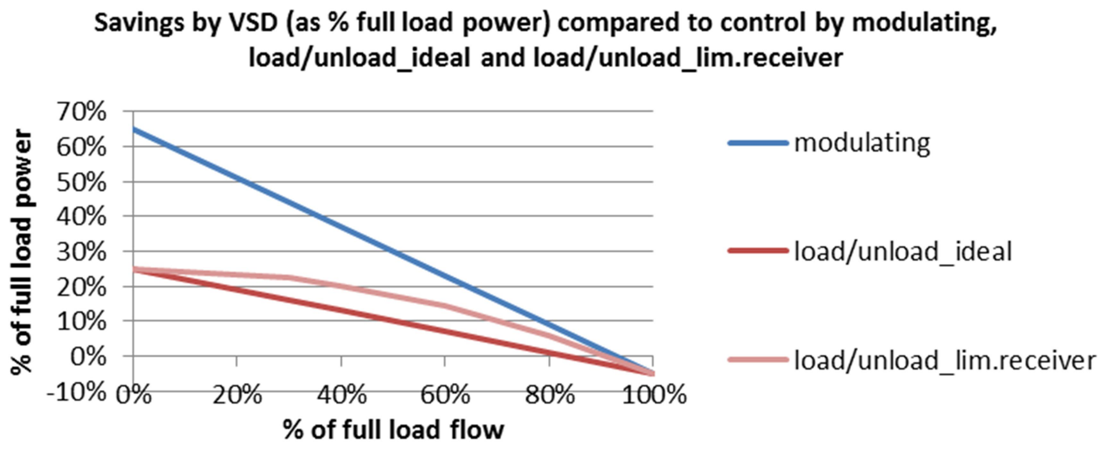
The relative savings of a VSD are largest for average volume flows further away from the full flow.

---

[184] http://hydraulicspneumatics.com/200/FPE/SystemDesign/Article/False/6462/FPE-SystemDesign

[185] VHK interpretation of several sources, see for instance: http://www.airbestpractices.com/system-assessments/compressor-controls/optimizing-specific-power-part-loaded-compressed-air-systems. The lines do not extend all the way down to 0% flow, as various control methods may be combined at these lower flows (load/unload with start-stop, VSD with load/unload, etc.).

Figure 68 Savings for applying a VSD compared to other control methods



The above relations and various other sources put the savings by a VSD anywhere between 5% to 35%[186]. For the calculation of savings VHK will assume a generic indicative saving of 10%. The savings are calculated by changing (reducing by 10%) the load factor[187] of the application so that the package efficiency and rated power input remain unaffected.

The cost effect of a VSD is linked to its power. The Lot 30 preparatory study on electric motors provided the following information.

Table 95 Prices of VSD's[188]

Description	Power (kW)	Unit Price (€)	Installation Costs (€)
VSD	0.12-0.75	200	50-300%
	0.75-2.1	280	50-250%
	7.5-45	1130	50-200%
	76-110	5320	50-175%
	375-1000	41790	50-150%
Soft Starter	1,1	60	30
	11	100	70
	110	800	100
Contactors	1,1	12	20
	11	30	30
	110	140	40

[186] Direct energy savings by applying VSDs in compressor applications are between 5-35% according a major VSD supplier: http://www.abb.com/cawp/seitp202/d8c203f60e3796adc12578a200580d94.aspx. Other sources state a similar range in savings.

[187] The load factor is a factor that reduces the power input at full flow to a power that resembles more closely the average power input over the entire operating hours.

[188] Anibal de Almeida et al, "Electric Motors and Drives, Task 2: Economic and Market Analysis", ENER/C3/413-2010, Final, April 2014, Table 2-19 (with reference to CEMEP and CAPIEL)

VHK calculated on the basis of these prices, an indicative power/price relation, expressed as a polynomial:

Equation 16 VSD costs (EUR) by power (kW)

$$\textbf{VSD costs} = 0.095 \cdot \text{Power}^2 + 50 \cdot \text{Power} + 200$$

Where:

VSD costs = the cost of applying a VSD (EUR/unit)

Power = package input power (kW)

Table 96 Comparison VSD costs Lot 30 and this Lot 31 study

VSD for power range [kW]	Unit price [EUR]	Avg. power [kW]	VSD Price (polynom.) [EUR]
Lot 30 report, power range (kW)	Lot 30 report (EUR)	VHK input values for power (kW)	VHK calculation (EUR)
0.12 - 0.75	200	0.5	225
0.75 - 2.1	280	1	250
7.5 - 45	1130	25	1509
76 - 110	5320	90	5470
375 - 1000	41790	450	41938

The cost/benefit of a VSD has been calculated for fixed speed (zero flow) categories only, as the other groups already have some form of flow control (can be VSD). As the category LP_ZFCRpeak is mainly used for pneumatic conveying this category cannot benefit from flow control as speed cannot be allowed to drop or the conveyed matter will drop out of suspension and start to clog the pipe. Therefore the VSD option does not apply to LP_ ZFCRpeak.

When increasing purchase prices with VSD costs and assuming a (general) saving of 10% the overall costs are reduced by some 5% to 8%. The VSD costs are recovered in 2.4 to 4.7 years (simple return on investment, calculated as extra costs divided by annual savings).

Table 97 Cost / benefit of VSDs for zero flow control range categories

Change in costs (EUR/life)	Power (kW)	Extra purchase costs "+VSD"	Savings "+VSD"	Energy costs "+VSD" over life	Difference over life	Share of total LCC (excl. refurb/disp.)	Return on investment (years)[189]
LP_WFCR	29.4				(not applicable)		
LP_LFCR	58.4				(not applicable)		
LP_ZFCR	8.9	653	10%	-2,342	-1689	-5.2%	4.7
LP_ZFCRpeak	23.5				(not applicable)		
OF_WFCR/a	26.3				(not applicable)		
OF_WFCR/w	162.3				(not applicable)		
OF_LFCR	185.0				(not applicable)		

[189] The return of investment calculated is the simple payback and only applies to the situation as presented. In real-life other payback rates may be possible due to differences in various conditions.

OF_ZFCR/a	13.7	902	10%	-4,761	-3859	-5.8%	3.8
OF_ZFCR/w	80.4	4832	10%	-38,298	-33466	-7.7%	2.4

VSD's do come with additional installation costs. The Lot 30 Ecodesign preparatory study on electric motors and drives assessed VSD installation costs to be between 50-300% of the VSD purchase price. For simplicity in this study a mark-up of 100% of VSD purchase price was assumed for installation costs.

6.3.2 Applying heat recovery

Perhaps the single most effective energy saving strategy for compressed air energy use is recovery of (waste) heat. The disclaimer for this option is that these savings can only be realised if indeed the waste heat is displacing energy consumption of other processes like space heating, water heating, process heating or drying etc.

As the recovery of heat takes place outside the package boundaries it is difficult to unlock these possible savings by product measures only. However, product design can influence the decision making process for recovery of waste heat by minimising the need for technical changes at the compressor side and by promoting the option in general sense.

For this reason the assessment presents a indicative calculation of waste heat recovery potential. It considers possible costs and benefits but is however not a design option in the traditional sense.

The heat recovery potential is as described in section 4.6.3. The costs of modifying the equipment to allow heat recovery differs per cooling technology mainly.

Air-cooled equipment can relatively easily be modified for heat recovery by ducting the cooling air from the package towards a useful application, usually space heating, combined with the necessary control elements like temperature sensors and diverters. The required changes for the compressor package are minimal as attaching a duct to the bodywork (sound canopy) of the package is fairly simple.

Modifying water-cooled equipment can be as simple, but could also entail adding an extra heat exchanger to transfer heat from the cooling water to the other application depending on the need to be able to switch between heat sources and/or heat sinks: As the temperature drop and flow rate across the heat exchangers are related and affect the main compressor and process parameters, the process of heat recovery has to be controlled to ensure safe, reliable and efficient operation of the whole package. Often manufacturers sell dedicated heat recovery units with heat exchangers, (3-way) valves, bypasses, taps and control gear integrated.

The direct costs for package modification to enable heat recovery from water-cooled compressors could not be determined on the basis of publicly available material and costs for dedicated heat recovery units were not available. Assuming that the size of the additional heat exchanger is probably the most expensive component a simple cost assessment is set up.

A 20 kW oil cooler costs 1000 USD (street price)[190], a 150 kW brazed plate heat exchanger is 2600 USD and 337 kW is 7000 USD [191]. The following relation can be concluded:

Equation 17 Costs for HR heat exchanger only, in EUR/heat exchanger

$$\textbf{Heat exchanger costs} = \mathbf{900 * e^{(0.006*Power)}}$$

Where:
Heat Exchanger costs = costs for heat exchanger (EUR)
Power = Package input power (kW)

[190] http://www.ecompressedair.com/compair-100001571-oil-cooler-replacement.aspx

[191] http://store.industrialairpower.com/Water-Cooled_c_305.html

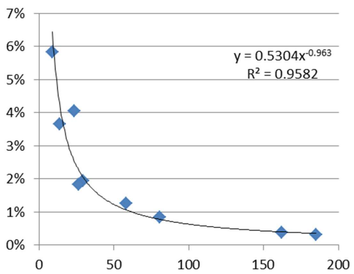
The cost ranges from some 3% of the larger equipment to over 10% for the smallest equipment (as % of the purchase price). The addition of other equipment (valves etc.) and design changes will probably result in doubling the above costs, to over 6% for the largest and 20% for the smallest equipment. These costs can be expressed as % of Purchase price, taking into account the size of the equipment.

Equation 18 Costs for heat recovery, in EUR/heat exchanger

$$\textbf{HR Cost (\% of purchase price)} = \mathbf{0.776 * Power^{-0.478}}$$

Where:
HR costs = costs for heat recovery (EUR)
Power = Package input power (kW)

Figure 69 Share of HR costs expressed as share of energy costs (base case)



The cost assessment however does not include or cover all costs related to heat recovery, such as ductwork for air cooled equipment, or controllers for regulating flow over heat exchangers of water-cooled equipment. For air-cooled equipment it is assumed that costs cannot be attributed to purchase costs as the necessary modifications are taking place beyond the package boundaries.

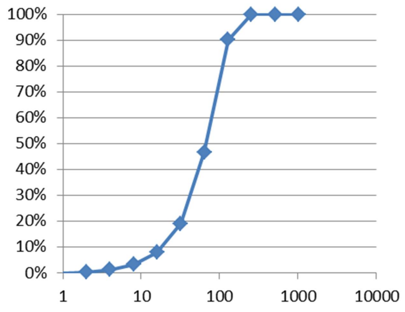
To account for this, the share of HR costs attributable per flow category is varied on the basis of share of water-cooled equipment (varies with average power).

Table 98 Share of HR purchase costs attributable

Flow category	% of purchase costs attributable
LP_WFCR	17%
LP_LFCR	42%
LP_ZFCR	4%
LP_ZFCRpeak	13%
OF_WFCR/air	15%
OF_WFCR/water	98%
OF_LFCR	99%
OF_ZFCR/air	6%
OF_ZFCR/water	61%

The reason that for "air-cooled" equipment the share is not zero is that the division into "air-" and "water-cooled" has been based on assumptions. It may be that actual sales and power is slightly different than presented. The division into air/water-cooled is not based on actual sales, therefore some of the capacity represented by the air-cooled group may be water-cooled.

Figure 70 Share of water-cooled equipment per power



Most of the costs for heat recovery will however not be linked to the components added to the compressor package but will be linked to the complete installation which has to be bespoke for each application. These bespoke costs should however not be attributed to the compressor package as these cannot be enforced through a horizontal product legislation (applying to all products within scope as they are placed on the market). Therefore only a limited share of installation costs, directly linked to making connections at the compressor package should be added.

In practice this is probably the realisation of a feed and return water connection for water-cooled equipment and (most probably) attaching a duct to the cooling air exhaust grille (or louvres) from an air-cooled machine. No such data was available in the public domain. Therefore the authors have assumed that the (package related) installation costs for heat recovery are similar to the purchase costs of the (additional) components for heat recovery, quite similar to how VSD installation costs are included (see previous section).

Fuel shift

Use of heat recovery assumes that there is a useful purpose for the heat recovered and assumes that this heat was generated with heaters anyway, if no recovery would have taken place. The question is what kind of heaters are replaced through use of heat recovery.

In general terms the most cost effective form of heating (applications with low electricity costs and no access to gas grind left aside) is fossil fuel (mostly gas) fired heaters . It is therefore assumed thatsavings through heat recovery are displacing primary fuels. When compared at this level, the overall savings are reduced.

Table 99 Calculating the actual savings for heat displaced through heat recovery

	Heat recovered = heat demand of reference heating	Conversion efficiency	Primary fuel conversion	Heat demand expressed in primary fuel requirement
If reference system is electric heating	100	100% (electricity to heat)	2.5	(100/100%)*2.5 = 250
If reference system is gas heating	100	70% (gas to heat[192])	1.0	(100/70%)*1.0 = 143

[192] This is an estimated average value, based on typical efficiencies found in the Ecodesign Lot 2 preparatory study on Water Heaters.

Relative savings if displacing gas fired equipment	Instead of 250 primary fuel units saved the recovered heat represents 143 primary fuel units if the reference heating system is gas-fired. The savings through heat recovery are therefore not 100% of the energy used, but 57% (143/250) of that.

The energy saved through heat recovery is therefore accounted for as 57% of the heat recovered (electric energy).

6.4 Side effects

The abovementioned measures may result in possible positive (apart from energy savings) or negative ('rebound') side effects of the (individual) design measures. These have been described below. Rebound effects that go beyond the direct sphere of influence of the product are not assessed.

Improved package efficiency

A side effect of improved package efficiency may be that the number of configurations allowed on market is reduced – and this may result in certain operating ranges (conditions) not being covered by available packages.

The reduced offering could result in losses of sales for manufacturers. If the customer can no longer buy the equipment that suited his/her application, he/she may be forced to buy multiple pieces of smaller equipment, or a single larger piece of equipment (oversized, running in part load more often) to meet their demand for compressed air. This may result in increased energy consumption for this specific application.

Secondly, if specific technologies would be banned from the market due to minimum efficiency requirements that could not be met with sensible efforts, the customers until now using these products (e.g. especially because of unique second performance characteristics) would be forced to look for other technologies. That might lead to increased complexity and expenditures (=suboptimal solutions) for the customer.

Applying VSD's in fixed speed categories

Applying a VSD is not a design option in the traditional sense, as packages with VSD's belong in the WFCR or LFCR categories and are covered separately from zero flow control range equipment.

The option assumes that a suboptimal match is made between (fixed speed) equipment and air demand, and that savings can be achieved by buying a VSD driven package instead. Side effects may be that if:

- the equipment spends only a very limited amount of time in unloaded state, the savings by applying VSD's are limited, if not negative, leading to extra costs.
- the customer operates compressors in fixed speed only, a VSD would introduce extra losses (between 4-10%).

Applying heat recovery

Application of heat recovery is not a design option in the traditional sense, as the benefits are highly dependent on system level aspects.

Nonetheless, the energy savings through heat recovery, if applied, can easily surpass savings from improvement of the energy efficiency of the package. Side-effects can be.

- HOC (Heat Of Compression) dryers use hot air from the package to regenerate the desiccant cores. These compressors are not equipped with an aftercooler and thus not compatible with heat recovery. Applying heat recovery will mean that another, more energy intensive, form of drying needs to be applied. The HOC dryer does introduce an extra 5-7 psig pressure loss (0.3 – 0.5 barg), but this has to be compared to pressure loss using other type of dryers.

- More efficient compressors generally produce less heat. It can be imagined that a plant engineer seeking to add (or replace) a compressor is simultaneously looking for a heat generator system. Under certain conditions it may be cheaper to acquire a less efficient compressor as this compressor would be able to fulfil the heat demand, whereas a more efficient compressor would not. In this example there would be no savings at package level, but possible savings at system level.

6.5 Environmental impacts of energy saving options

Given the dominance of energy consumption in the environmental profile, it is not expected that any extra material required for achieving savings will significantly change the environmental profile.

6.6 Non-energy options

Apart from the options that aim to save energy there may be options that aim to reduce other, non-energy, impacts. These are referred to as 'material efficiency'.

Material efficiency may in general be improved by:

1. light weighting;
2. extension of product life (reparability);
3. reuse of parts/components;
4. recoverability / recyclability and recycled content.

Several design options address the above aspects:

- There are profound differences in mass of a (high speed) turbo compressor and a positive displacement compressor offering similar performance: the high speed turbo compressor is lighter (***light weighting***) and has fewer moving parts which reduces needs for maintenance/repair (***product life***). Most manufacturers already optimise for longer product life as in most cases for a customer the costs for downtime are much higher than the running costs of the equipment.
- As regards reuse of components, it should be said that refurbishment (also referred to as reconditioning, etc.) is quite common, and the industrial air compressor should not be compared to various domestic products in this regard. Air compressors represent a major investment in general and parts and components are re-used when economically viable.
- Modern compressors do have more electronics in them than before. Besides motor control drives, electronics are now also found in magnetic bearings. This brings us to the subject of recyclability and the presence and recovery of raw materials in particular.
- Electric motors may have critical raw materials (neodymium in permanent magnets) in them, and the control gear (motor drivers, switches, displays, I/O terminals) have electronics that may contain several critical raw materials.
    - The use of “super premium” or “IE4” induction motors, which appear to only recently have been made available commercially, is still not widespread according to the 2016 DOE study[193] .
- Although large scale stationary equipment such as compressors do not fall within the scope of the WEEE, there are lessons to be learnt such as:
    - making parts that carry a significant or relevant amount of valuable resources easy to disassemble: this goes for motors, displays, and other electronics;
    - avoid use of hazardous or other harmful substances, like mercury (in lighting or switches), cadmium, lead (in PCBs) and also avoiding use of brominated flame retardants in plastic parts as this reduces the options for further recycling;

[193] Many of these improvement options have also been identified in the DOE background document, p. 3-45, 77/643.

- identification of parts/components that contain critical raw materials, such as motors, displays, PCB's, etc.

However, as the Ecoreport analysis has shown, the material consumption is not the dominant environmental parameter and care should be given that any improvement of material efficiency does not negatively affect energy efficiency, nor the main functionality and safety of the product.

TASK 7: Policy options

7 Policy options

7.1 Introduction

In this Task 7 policy options for reducing environmental impacts of the products are analysed. Possible impacts are assessed and quantified using scenario analysis.

A sensitivity analysis of the main parameters checked the robustness of the outcome, regarding energy prices and societal costs.

7.2 Policy analysis

7.2.1 Stakeholder consultation during study

Stakeholders in industry, NGO's as well as Member States have been asked to participate in this study, and over 100 stakeholders have registered themselves through the project website:

www.eco-compressors.eu

The study allowed continuous stakeholder consultation. Documents are freely accessible.

A first open stakeholder meeting was organised on 26 April 2016 and focused on (draft) task 1, 2 3 and 4.

A second stakeholder meeting was organised on 6 March 2017 and focused on the complete report Task 1 to 7.

During the study several meetings between the consultants and a group of industry experts (collaborating as Joint Working Group Ecodesign under Pneurop administration) took place to discuss specific technical details of the study.

7.2.2 Barriers and opportunities for improvement of environmental impacts

Task 5 shows the main environmental impact of low pressure and oil-free compressors is the energy consumption during use. There are several opportunities to reduce this consumption or otherwise achieve energy savings.

The most direct option is to improve the **package efficiency**. Task 4 showed that sufficient disparity between products exists. Task 6 showed that improved energy efficiency is cost-effective. Barriers however exist: Improving package performance may drive up costs (of product or for manufacturers) and may result in a reduced market offering. There is a risk that, in case of applications requiring products that are no longer on offer, this could lead to suboptimal solutions (too large or multiple smaller equipment being bought/run).

Another option is to improve the understanding of customers of the **saving potential of VSD's** in applications with significant part load conditions or fluctuating air demand. There are no technical barriers in the sense that equipment can be bought with variable flow capability. The biggest barrier to overcome is the awareness of customers of their air demands (in size, in time, etc.).

There are examples of Ecodesign measures where the use of VSDs is directly promoted: The electric motor regulation required as minimum efficiency IE3 motors, or IE2 motors if sold with VSD. The measure for industrial fans included a compensation factor for use of VSD's (compensating the additional electric losses introduced by the VSD).

Such 'bonuses' do not match with an approach that recognises variable flow equipment as a separate category, with possible less strict requirements. Differentiating minimum energy efficiency requirements between zero flow and variable flow categories already imply a sort of bonus as the two groups are treated differentially. The fear that manufacturers use variable flow control categories as loophole by adding flow control devices to fixed speed devices just for meeting requirements, is highly unlikely as such devices always create extra effort and costs, making this route less attractive. Therefore, a bonus-approach, as applied in the 2009/640/EU Motor regulation is not called for.

The most promising option, with the highest saving potential arguably, is **recovery of heat**. Here the largest barrier is probably the need for both a supply AND demand for heat, so that a match can be made (in size, in location, in distribution profile, etc.). Heat recovery can already be applied, but often requires additional equipment and possibly some modifications on the compressor unit. It is especially this latter aspect that may be improved through measures.

7.2.3 Pro's and con's of (combinations of) policy instruments and overlaps with existing legislation

The policy instruments available to legislators to improve the environmental characteristics of products are: Voluntary agreements, Ecodesign measures, both generic and specific, Energy labelling and a combination of measures, including awareness raising.

Voluntary measures need to be driven by the relevant industries to commit to self-imposed targets, that are not unlike specific measures in effect. The number of participants and market coverage needs to comply with minimum provisions. So far, the industries involved have not expressed an interest in a voluntary agreement.

Energy labelling is primarily aimed at providing laypersons an indication of relative energy efficiency at the point of sale (brick shop or web shop). As compressors are mostly supplied to client specifications, energy efficiency can be integrated in the specification process. This situation is not comparable to a person wandering in a retail outlet and Energy Labelling is not considered as policy option for further analysis. Information on efficiency can be required under Ecodesign measures as well.

Ecodesign measures allow the legislator to impose minimum energy efficiency requirements, information requirements (or other specific measures) to which the product must comply before it may be placed on the EU market. This policy option will be further analysed.

Not a measure in the strict sense as it does not fall under Ecodesign or Energy labelling is **awareness raising**. Examples of awareness raising campaigns organised by the EU are the EU Motor Challenge program [194] and the Build-Up program (for improving the building stock of the EU). As heat recovery and application of variable flow equipment is typically something that would come up during an energy audit, the relevance of the Eco-Management and Audit Scheme (EMAS)[195] and Best available techniques Reference document (BREFs) [196] should not go unnoticed.

Measures (rules) that already apply to low pressure and oil-free compressors mainly relate to safety (CE marking through the Machinery Directive and other safety Directives such as the Low Voltage Directives). Ecodesign or flanking measures will not be in conflict with these existing measures.

7.2.4 Policy options for further analysis

The following policy measures have been selected for further analysis:

- minimum energy efficiency requirements combined with information requirements (specific Ecodesign measure);
- awareness raising for increased uptake of VSD driven compressors;
- preparing the package for possible heat recovery (specific Ecodesign measure), combined with awareness raising.

Definitions of products and relevant performance standards have been identified under Task 1.

[194] http://iet.jrc.ec.europa.eu/energyefficiency/motor-challenge-programme/tools

[195] http://ec.europa.eu/environment/emas/index_en.htm

[196] http://eippcb.jrc.ec.europa.eu/reference/

7.3 Scenario analysis

7.3.1 Baseline (Business-as-Usual BaU)

The impacts (energy savings, increased costs) achieved by the various policy options are assessed against a business-as-usual (BAU) scenario, which describes the situation with no new policies, assuming that existing trends continue.

The BAU scenario is based on sales and stock data of Task 2 and efficiency data of Task 4 (for year 2015).

Figure 71 Sales and capacity of LP vs. OF, in BAU scenario 2015

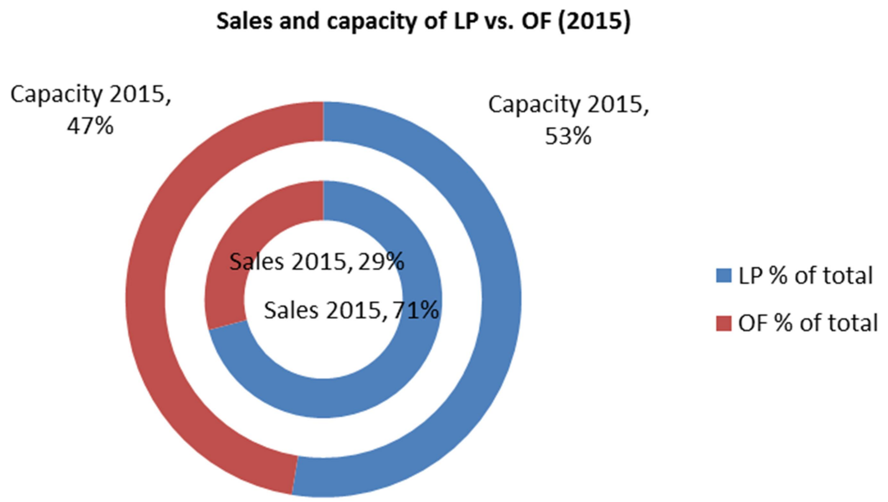
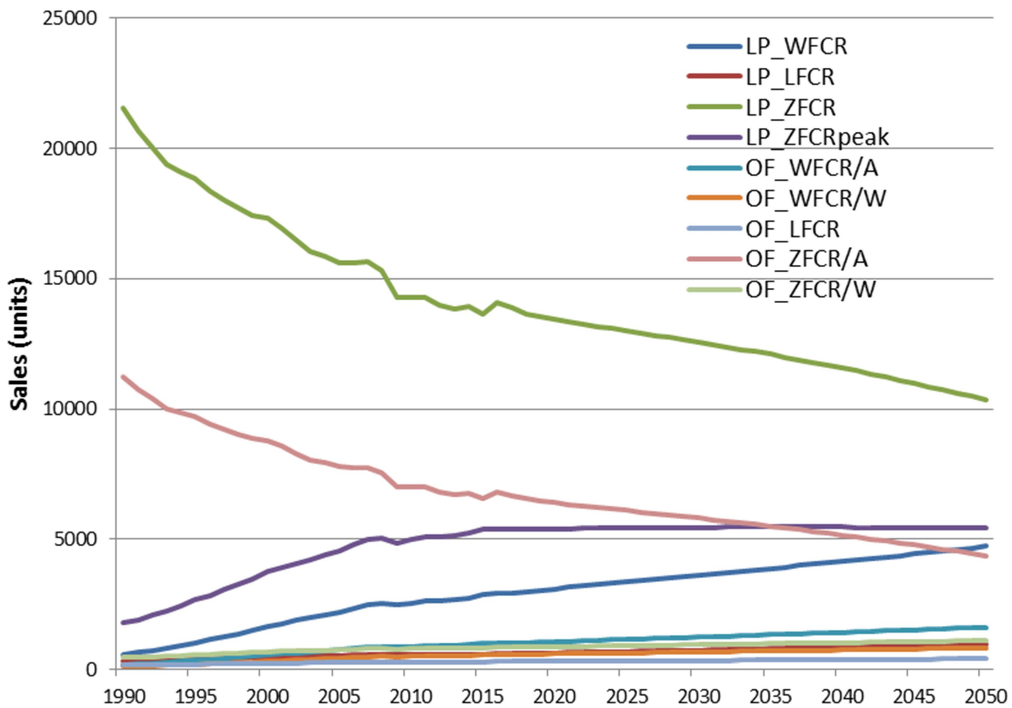


Figure 72 Sales (pieces/a) for the BAU scenario



VHK has extrapolated the efficiency of the average product sold (as established in Task 2) to historic and future years. The figure below shows the relative change in efficiency (2015 = index 100).

Figure 73 Efficiency (index 100 = 2015) for the BAU scenario 1950-2050

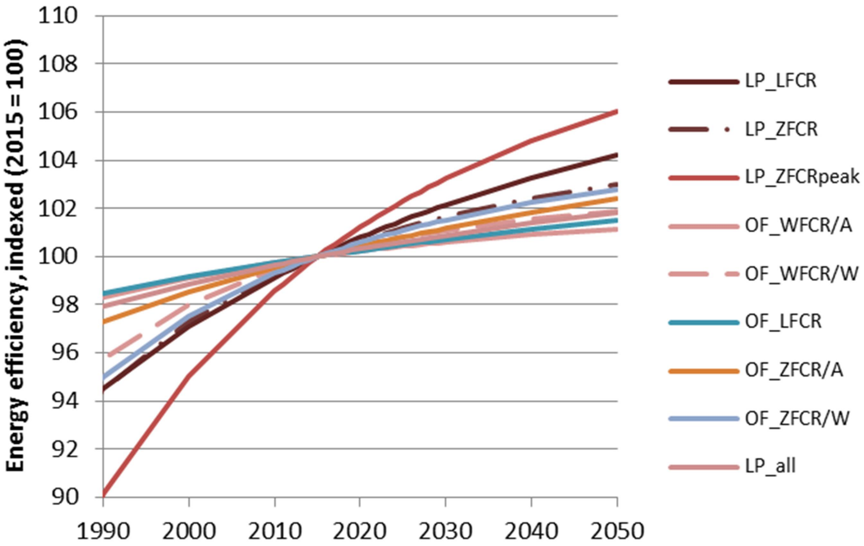
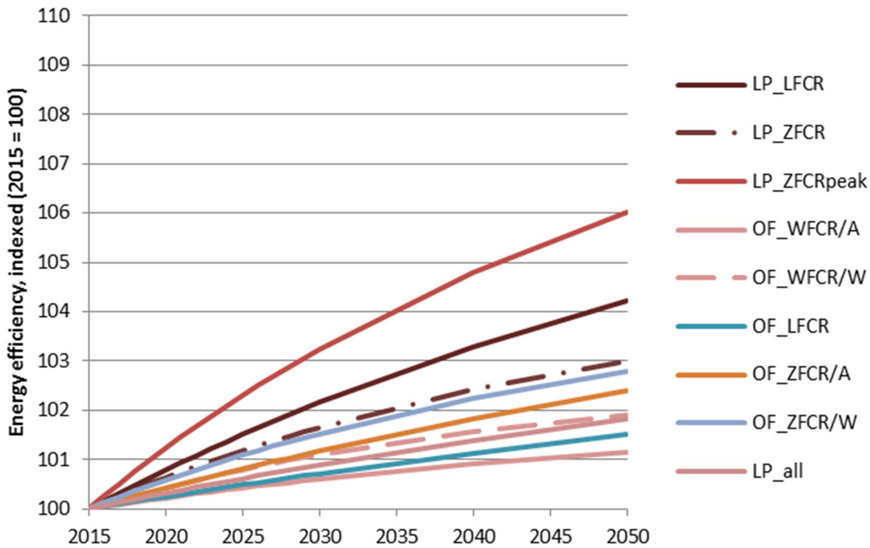


Figure 74 Efficiency (index 100 = 2015) for the BAU scenario – close-up 2015 and beyond



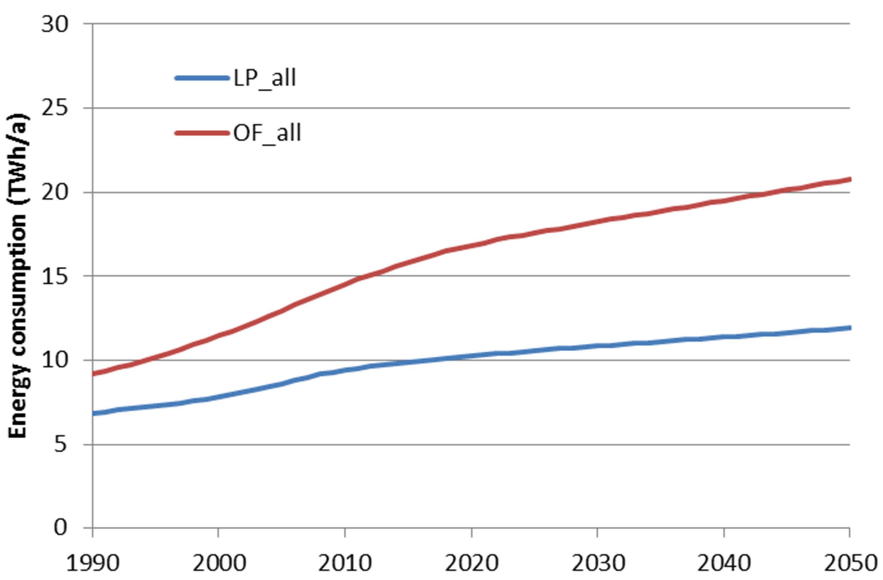
The energy consumption according the BAU scenario is shown below. The BAU assumes an optimistic development[197] of GDP (which governs the future sales volume).

[197] The development of GDP is explained in Task 2, section 2.3.1., "Sales 1990-2050".

Table 100 Energy consumption (TWh/a) for the BAU scenario

Flow categories	Year						
	1990	2000	2010	2020	2030	2040	2050
LP_WFCR	0.3	1.2	2.5	3.2	4.1	4.9	5.7
LP_LFCR	0.6	1.0	1.3	1.4	1.8	2.1	2.5
LP_ZFCR	5.5	4.4	3.5	3.1	3.1	3.0	2.7
LP_ZFCRpeak	0.4	1.2	2.1	2.6	2.9	3.1	3.1
OF_WFCR/air	0.1	0.4	0.8	1.1	1.4	1.7	2.0
OF_WFCR/water	0.4	1.6	3.6	5.3	6.6	7.8	9.0
OF_LFCR	1.1	2.1	3.1	3.6	4.2	4.9	5.5
OF_ZFCR/air	6.4	5.3	4.1	3.5	3.3	3.2	2.8
OF_ZFCR/water	1.1	2.1	2.9	3.4	3.9	4.5	5.0
LP_all	6.8	7.8	9.4	10.4	11.8	13.1	14.1
OF_all	9.2	11.5	14.5	17.0	19.4	22.1	24.4
LP+OF	16.0	19.3	23.9	27.3	31.2	35.2	38.6

Figure 75 Energy consumption (TWh/a) for the BAU scenario



The BAU consumption calculated for 2015 for low pressure packages is some 10 TWh/a. For oil-free packages it is some 15 TWh/a. These two application ranges thus represent max. 1% of the total EU28 electricity consumption (2800 TWh).

7.3.2 Policy option scenarios + main impacts

Minimum energy efficiency requirements

Three variants in minimum energy efficiency requirements have been assessed. The variants have been constructed to result in an certain impact on the sales (expressed as percentage of sales affected by the measure). A certain minimum energy efficiency, expressed as minimum D-value to be achieved, results in a certain share of models not being compliant anymore (the "sales affected"). As the BAU also assumes a continuous improvement of energy efficiency, the BAU scenario by itself will result in a certain share of 'sales affected'. The difference between the 'sales affected' calculated for the scenario's and the BAU is the 'actual sales affected' which is used as target in the below definition of scenario's.

The industry experts provided VHK with an assessment of performance and sales of products. Based on this assessment the average efficiency of the products and the relation between a change in D-value and savings (to be interpreted as setting a target minimum efficiency) was described.

It is assumed that the compressor load (calculated on the basis of flow rate, inlet and outlet pressure, load factor and annual operating hours) does not change. A change in efficiency will therefore have a proportional effect on the power consumption only (and annual energy consumption).

As the exercise is based on sales-weighted values, simply removing the sales of equipment below a given target efficiency (expressed as D-value) would not be realistic, as the demands for compressed air would still be present and have to be met by equipment placed on the market.

To overcome this, industry experts agreed to assume that the sales replacing the non-compliant equipment sales would be at either 20% or 40% of the range between the average (D=0) and BAT (D-value of BAT depends on flow control category, often around 20-30). This is called the 'replacement factor' of either 0,2 or 0,4.

The savings achieved over the sales population (of the flow control categories selected) were calculated from the data collection in relation to the D-values applied. VHK represented the curves extracted from this information using a generalised logistic function[198] over the available data points and have Excel SOLVER find the best fit for the parameters of the logistic function.

Equation 19 Generalised logistic function used to represent Percent savings per D-value

$$Y(t) = A + \frac{K - A}{(C + Qe^{-B(t-M)})^{1/v}}$$

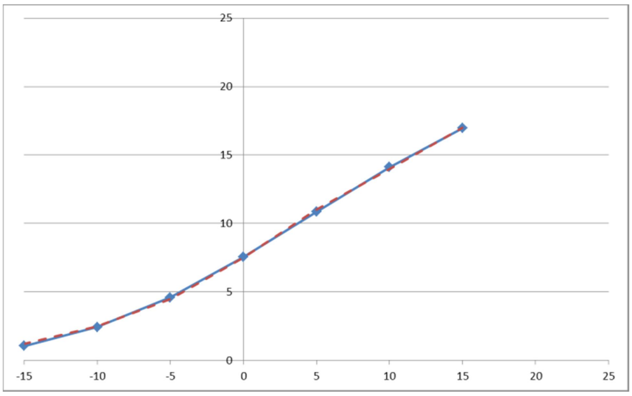
Where:

Y(t) = the parameter to be described, here "% saved compared to no D-value applied";

t = D-value
A = lower asymptote
K = upper asymptote
B = growth rate
v >0 = affects near which asymptote maximum growth occurs
Q = related to value Y(0)
C = typically takes a value of 1
M = starting time of ascending value

The figure below shows an example of the curve fitting method described above. applied.

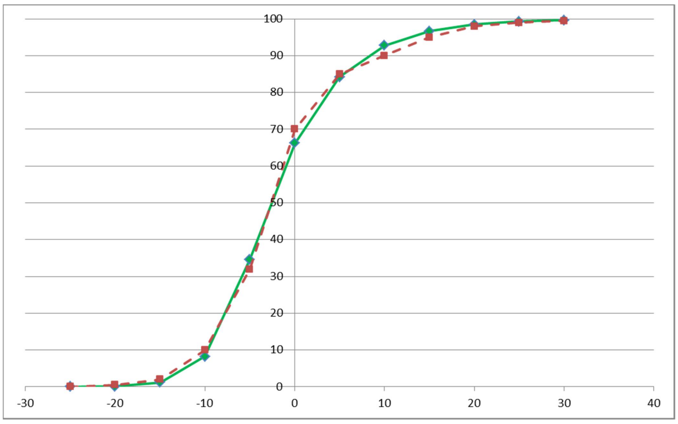
Figure 76 Example of 'savings curve' for LP_ZFCR (replacement factor 0.2)



[198] https://en.wikipedia.org/wiki/Generalised_logistic_function

Note: The blue dots/line present the saving (%) calculated for each D-value implemented, the red curve is the approximation using the generalised logistic function.

Figure 77 Example of 'sales affected curve' for LP_ZFCR



The parameters that gave the best fit for the individual flow control categories are:

Table 101 Curves describing relation D-value/savings and % saved

Category	replacement factor	Parameter						
		A	K	C	Q	B	M	v
LP_WFCR	0.2	202.6148	0.356379	0.809108	2.819562	0.122582	1.30688	62.148
LP_LFCR		113.4861	0.001408	1.005201	1.914185	0.097875	0.16642	30.53523
LP_ZFCR		27.88944	2.750058	0.703833	1.131493	0.147135	0	2.874819
LP_ZFCRpeak		24.08342	1.236456	0.76364	1.176536	0.21355	1.224435	5.269749
OF_WFCR/A		100	0	1	0.91	0.35	-8	90
OF_WFCR/W		258.5276	0.12979	0.875332	18.09919	0.444709	0.846132	398.1733
OF_LFCR		64.67589	0.571496	0.645763	5.938527	0.18109	1.104004	53.33318
OF_ZFCR/A		273.0655	0.422859	0.694999	22.693	0.461431	0.826508	265.4453
OF_ZFCR/W		75.56287	0.328763	0.719062	3.417065	0.199194	1.171349	56.30925
LP_WFCR	0.4	156.4498	0	1.575629	278.1392	0.330732	0	175.508
LP_LFCR		21.10518	0.000131	1.018311	2.838714	0.102819	0	5.421671
LP_ZFCR		23.7794	0.727877	0.863463	5.05072	0.217374	3.29E-08	3.502273
LP_ZFCRpeak		18.64002	1.411469	0.69122	2.127429	0.256579	0.465779	5.230168
OF_WFCR/A		100.000	0.000	1.000	0.910	0.350	-9.000	90.000
OF_WFCR/W		29.2052	0.215432	0.792226	47.69385	0.506704	5.25E-09	49.26571
OF_LFCR		15.32745	0.080218	0.934406	3.141526	0.127132	0	6.382937
OF_ZFCR/A		14.42919	0	0.984659	7.564861	0.335792	0	6.110352
OF_ZFCR/W		15.7552	0	0.855955	5.093791	0.19662	0	9.062737

The parameter values for the 'sales affected' are:

Table 102 Curves describing relation D-value and % 'sales affected'

Category	Parameter						
	A	K	C	Q	B	M	v
LP_WFCR	100.99	0.00	1.00	1.14	0.14	0.00	0.89
LP_LFCR	99.46	2.30	1.00	0.23	0.15	0.14	0.22
LP_ZFCR	100.00	0.00	1.00	17.73	0.42	0.00	2.70
LP_ZFCRpeak	99.26	1.95	1.00	0.19	0.17	0.00	0.18
OF_WFCR/A	100.00	-1450.00	1.99	0.10	0.12	-15.00	0.27
OF_WFCR/W	100.72	10.75	0.82	2.75	0.29	0.00	1.73
OF_LFCR	100.00	0.00	1.00	4.50	0.20	0.00	1.70
OF_ZFCR/A	100.00	0.00	1.01	10.00	0.50	0.00	2.00
OF_ZFCR/W	99.60	0.00	0.99	0.86	0.16	0.00	0.82

For all three variants the implementation date (date of entry into force of requirements) is set at 2021, approximately three years after a possible publication of Commission Working Documents in 2017 or 2018.

Table 103 Scenario I for minimum energy efficiency requirements – main impacts

Target 10% sales affected

Scen I	D-value		Savings (TWh/a)		
	(year 2021)	Sales affected (%) [199]	2030	2040	2050
LP_WFCR	-11	8%	0.016	0.018	0.017
LP_LFCR	-13	9%	0.010	0.010	0.009
LP_ZFCR	-9	10%	0.029	0.020	0.014
LP_ZFCRpeak	-10	9%	0.006	0.007	0.005
OF_WFCR/air	-7	11%	0.003	0.003	0.002
OF_WFCR/water	-6	8%	0.005	0.009	0.008
OF_LFCR	-12	9%	0.005	0.009	0.007
OF_ZFCR/air	-6	10%	0.005	0.004	0.002
OF_ZFCR/water	-8	8%	0.005	0.008	0.006
Totals					
Saved (TWh/a)			0.08	0.09	0.07
Saved (% of BAU)			0.3%	0.3%	0.2%

Table 104 Scenario II for minimum energy efficiency requirements – main impacts

[199] The percentages of 'sales affected' may deviate from the target value somewhat, as they are the result of calculating using a minimum efficiency expressed as D-value, which can be changed with an increment of 1 (one).

Target 25% sales affected

Scen II	D-value		Savings (TWh/a)		
	(year 2021)	Sales affected (%)	2030	2040	2050
LP_WFCR	-5	26%	0.05	0.06	0.05
LP_LFCR	-7	25%	0.02	0.02	0.02
LP_ZFCR	-6	26%	0.06	0.04	0.03
LP_ZFCRpeak	-5	27%	0.02	0.02	0.01
OF_WFCR/air	-4	24%	0.01	0.01	0.00
OF_WFCR/water	-3	25%	0.02	0.04	0.02
OF_LFCR	-7	26%	0.02	0.03	0.02
OF_ZFCR/air	-4	27%	0.02	0.02	0.01
OF_ZFCR/water	-3	26%	0.02	0.03	0.01
Totals					
Saved (TWh/a)			0.24	0.26	0.18
Saved (% of BAU)			0.8%	0.9%	0.6%

Table 105 Scenario III for minimum energy efficiency requirements – main impacts

Target 40% sales affected

Scen III	D-value		Savings (TWh/a)		
	(year 2021)	Sales affected (%)	2030	2040	2050
LP_WFCR	-1	39%	0.08	0.09	0.09
LP_LFCR	-3	40%	0.03	0.03	0.02
LP_ZFCR	-4	39%	0.08	0.06	0.04
LP_ZFCRpeak	-2	42%	0.02	0.02	0.01
OF_WFCR/air	0	39%	0.01	0.01	0.00
OF_WFCR/water	0	42%	0.04	0.05	0.02
OF_LFCR	-3	41%	0.03	0.05	0.02
OF_ZFCR/air	-2	41%	0.04	0.02	0.01
OF_ZFCR/water	0	38%	0.03	0.03	0.01
Totals					
Saved (TWh/a)			0.35	0.35	0.23
Saved (% of BAU)			1.2%	1.1%	0.7%

The assessment shows that electricity savings are less than 1 TWh/a, with a saving of maximum 0.4 TWh/a in the period 2030-2040 affecting approximately 40% of the sales at the year of implementation (2021). Other impacts are calculated in subsequent sections.

Applying VSD's in fixed speed applications

The scenario for applying VSD's in fixed speed applications applies to the ZFCR categories only as the LFCR and WFCR categories already assume some form of flow control (can be VSD). The LP_ZFCRpeak flow control category is excluded as it applies to pneumatic conveying mainly.

The calculation of savings achieved through increased uptake of VSD driven equipment is not calculated by simply transferring sales from the zero flow categories (ZFCR) to variable flow categories, as these categories have different average capacities (power in kW) and unit energy consumption: Transfer of sales volume from ZFCR to varibale flow categories would distort the overall projected capacity increase which governs the sales trends.

Instead the savings have been calculated by treating a (growing) share of stock units in the relevant zero flow categories as 'VSD driven' equipment, which affects their energy consumption and costs (see Task 6, section 6.3.1), but not that of the other flow control categories.

The saving to be achieved by VSD equipment versus single speed applications is set at 10% (see Task 4 'Part load operation'). The savings are calculated on the basis of a maximum of stock equipped with VSD, the year of implementation (when growth in stock is assumed to start) and a 'ramp-up' time (the time it takes for the stock to reach the target share) for the LP categories mentioned above.

The target for the share of stock equipped with VSD is set at 50%, as this is the share that motor industry experts expect as possible share of electric motors with VSD[200].

This means that the stock of zero flow categories LP_ZFCR, OF_ZFCR|A and OF_ZFCR|W the specific share in the stock must be reduced by a factor 0.5 as shown in the table below[201].

Table 106 Overview of how ZFCR stock shares are changed to achieve a 50% overall 'variable flow' share in stock

#	category	Share in stock (units 2015)	ZFCR shares reduced by 0.5	'New' share 'fixed' flow	'New' share 'variable' flow
1	LP_WFCR	9%			9%
2	LP_LFCR	2%			2%
3	LP_ZFCR	35%	(*0.5 =) 17%	17%	17%
4	LP_ZFCRpeak	19%	a)	19%	b)
5	OF_WFCR/A	3%			3%
6	OF_WFCR/W	2%			2%
7	OF_LFCR	1%			1%
8	OF_ZFCR/A	24%	(*0.5 =) 12%	12%	12%
9	OF_ZFCR/W	4%	(*0.5 =) 1.8%	1.8%	1.8%
Fixed flow categories 3, 8 + 9 and 4 (unsuited for VSD)		82%		50%	
Variable flow categories 1, 2, 5, 6 + 7		18%	to increase up to 'target' = (→)		50%

a) Category not suitable for enhanced uptake of VSD
b) Category should not be allocated to 'variable flow'

For the stock of variable flow equipment to reach 50% (of units installed) in 10 years time ('ramp-up'), the share of sales of (formerly) zero flow contral categories equipped with VSD's must increase to 42% for LP_ZFCR to 72% of sales of OF_ZFCR|W.

Table 107 Scenario IV for applying VSDs in fixed speed applications – main impacts

[200] Motor Summit 2016 Zurich, Global Overview, Conrad U. Brunner, Impact Energy and other expert opinions.

[201] The change is applied to number of units in stock and not installed capacity as the capacity of 'variable flow' devices already approach the 50% mark (in 2015 some 45% of installed capacity (sales*kW) is variable flow) and the calculated change (and resulting savings) would then be minimal.

Scen IV	VSD Saving potential	10%	Savings (TWh/a)		
Target stock share:	Year implemented	2021	2030	2040	2050
50% variable flow	Ramp-up time (y)	10			
	Sales share with VSD (%)				
LP_WFCR					
LP_LFCR					
LP_ZFCR		43%	0.14	0.13	0.11
LP_ZFCRpeak					
OF_WFCR/air					
OF_WFCR/water					
OF_LFCR					
OF_ZFCR/air		61%	0.15	0.14	0.12
OF_ZFCR/water		75%	0.18	0.20	0.21
Totals					
Saved (TWh/a)			0.5	0.5	0.5
Saved (% of BAU)			1.6%	1.5%	1.4%

The energy savings calculated for this option are approximately twice as high as Scenario II (target 25% sales affected) and 1.5 as high as Scenario III (target 40% sales affected).

Applying heat recovery

As discussed in Task 4 some 80-90% of the energy consumed by compressors is emitted as heat. The majority of this heat can in principle be recovered from the cooling air or cooling water of the compressor package, provided there is a 'sink' for this heat. Application of heat recovery is therefore very much specific to the characteristics of the equipment, the location and the process demanding the heat (see also section 4.6 on heat recovery potential and 6.3.2 on costs).

Similar to the 'applying VSD's' option, this option is calculated on the basis of a change in stock characteristics. The saving potential per flow category is described in Task 6. The number of installations using heat recovery is set at an increase of 20% of stock[202]. The year of implementation is set at 2021 and a ramp-up time of 10 years is assumed (changeover of stock at 2.5% per year). The heat saved is calculated as primary fuels, expressed as electricity (see section 6.3.2 'Fuel Shift').

Table 108 Scenario V for applying heat recovery – main impacts

Scenario V	Stock share with HR	20%	Savings (TWh/a)		
Flow category	Year implemented	2021	**2030**	**2040**	**2050**
	Ramp-up time (y)	10			

[202] The 20% value is chosen as it is similar to the value identified (for waste heat recovery) in the 2000 study "Compressed Air Systems in the European Union – Energy, Emissions, Savings Potential and Policy Actions" by Peter Radgen and Edgar Blaustein (Fraunhofer ISI), carried out for the SAVE Programme project XVII/4.1031/Z/98-266. See: www.isi.fraunhofer.de/isi-wAssets/docs/x/de/publikationen/c-air/web-version.pdf. As stated, the actual share of applications applying heat recovery depends on the possibilities found at these application sites and may be higher or lower than indicated.

	HR potential			
LP_WFCR	72%	0.3	0.4	0.4
LP_LFCR	72%	0.1	0.2	0.2
LP_ZFCR	90%	0.3	0.3	0.2
LP_ZFCRpeak	90%	0.2	0.3	0.3
OF_WFCR/air	72%	0.1	0.1	0.1
OF_WFCR/water	58%	0.4	0.5	0.5
OF_LFCR	72%	0.3	0.4	0.4
OF_ZFCR/air	90%	0.3	0.3	0.2
OF_ZFCR/water	72%	0.3	0.3	0.4
Totals				
Saved (TWh/a)		2.22	2.59	2.71
Saved (% of BAU)		7.6%	8.4%	8.3%

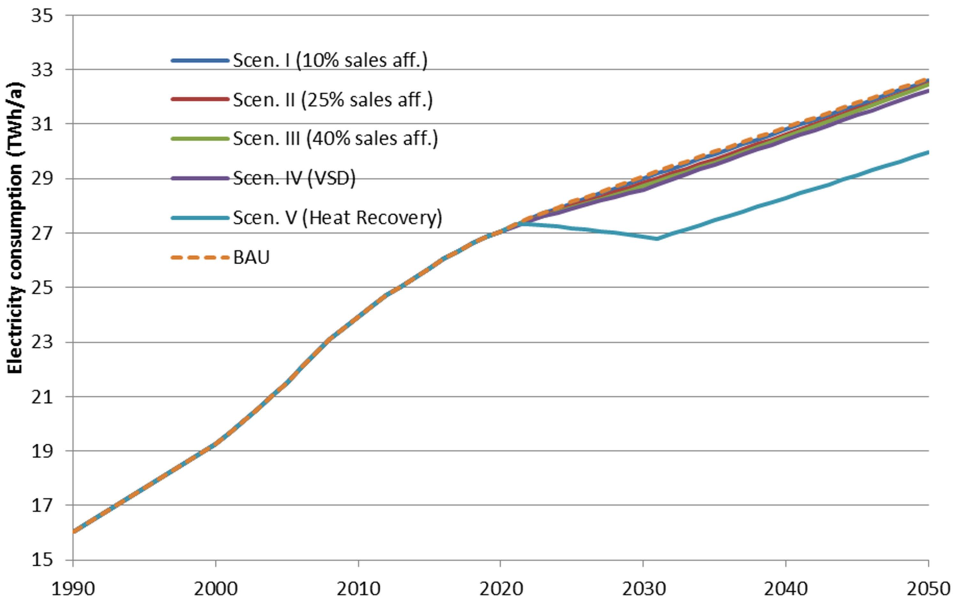
The savings to be achieved in such a program are 6 to 12 times larger than those achieved under strict minimum energy efficiency requirements (Scenario III).

7.4 Impacts on energy and environment

7.4.1 Energy consumption (electricity)

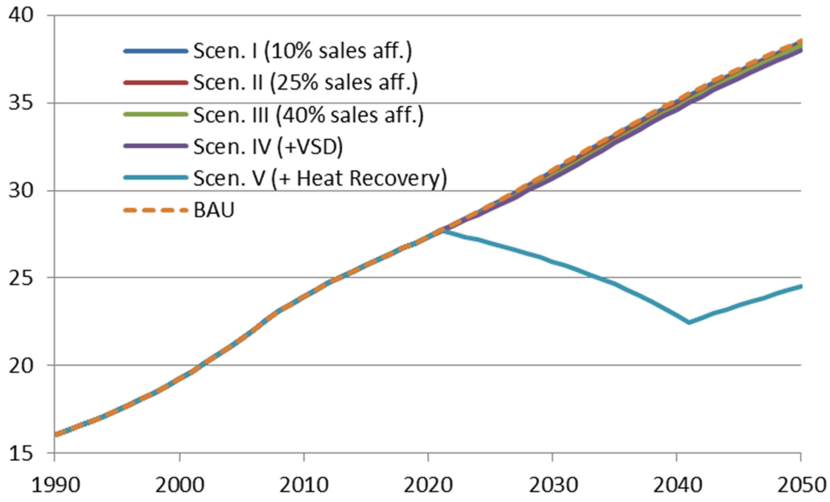
As to be expected the scenario involving recovery of heat (at level of 25% of stock, to be achieved in 10 years ramp-up time) achieves the highest savings. These savings may be achieved by either a high number of sales of products with heat recovery applied during installation, or can also cover conversions of existing equipment (applies to stock). The reason that the savings do not reduce further beyond the 10 year ramp-up, is that the scenario-settings assume a constant maximum heat recovery share applied after the end of the ramp-up time.

Figure 78 Electricity consumption for scenario I to V, in TWh/a



The recovery of waste heat of compressor packages is a measure that surpasses the saving potential by package optimisation only. If the recovery of waste heat would improve by 10% (from 0% to 10%, or from 30% to 40%) this alone would save some 2 TWh/a of heat (assuming some 20 TWh/a total electricity consumption). If this heat were to be generated with fossil fuels, the saving in primary energy is (assuming a fossil fuel heater efficiency of only 70%) would be almost 3 TWh of fuels.

Figure 79 Electricity consumption for scenario I to V, in TWh/a – for HR increase to 50% with 20 years ramp-up



7.4.2 GHG emissions

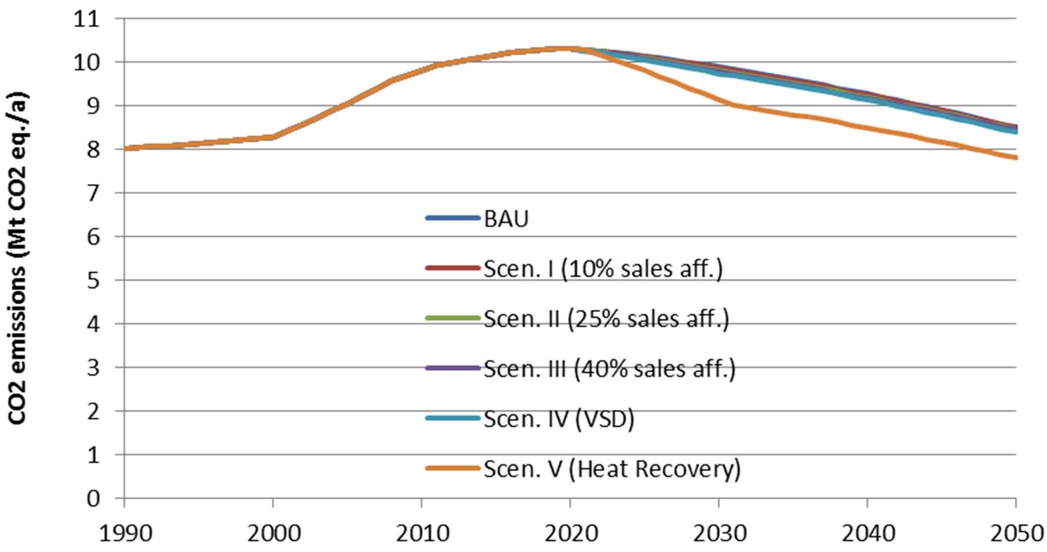
As all products covered are electric (scope of study) the greenhouse gas (GHG) emissions grow proportionally to energy (assuming emission rates as shown below).

Table 109 GHG Emission rates (kg CO2eq./kWh)

Year	1990	2000	2010	2020	2030	2040	2050
Emission rate (kgCO2eq./kWh	0.500	0.430	0.410	0.380	0.340	0.300	0.260

No other GHG emissions than those from electricity production have been considered.

Figure 80 GHG emissions (Mt CO2 eq.)



7.5 Impacts on industry and consumers

7.5.1 Industry impacts

Revenue

The model calculated an overall revenue of the LP and OF industry (which covers purchase, installation and service/maintenance, including refurbishment) in 2015 of approximately 5.2 billion EUR of which 44% is for LP and 56% for OF.

Figure 81 Industry revenue, including maintenance/refurbishment (million EUR)

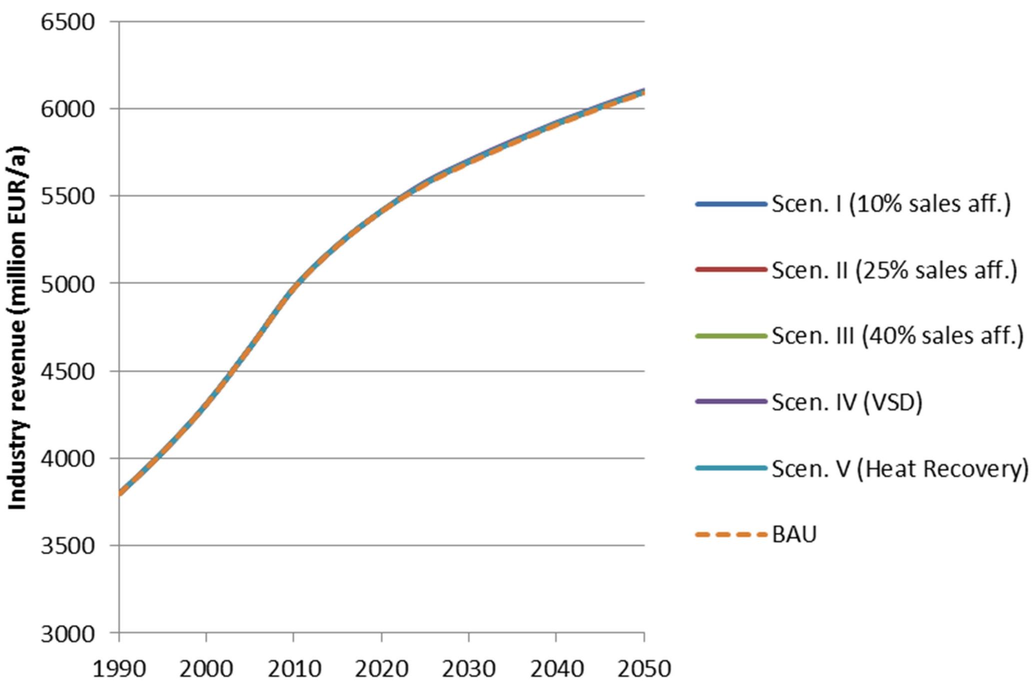


Table 110 Industry revenue (purchase + installation, VSD, HR, + maintenance, +refurbishment)

Industry revenue (million EUR)	2015	2020	2030	2040	2050
Scen. I (10% sales aff.)	5246	5442	5727	5949	6136
Scen. II (25% sales aff.)	5246	5442	5730	5951	6137
Scen. III (40% sales aff.)	5246	5442	5732	5952	6138
Scen. IV (+VSD)	5246	5442	5736	5958	6145
Scen. V (+Heat Recovery)	5246	5442	5731	5953	6137
BAU	5246	5442	5726	5948	6135
Difference to BAU (million EUR)					
Scen. I (10% sales aff.)			2	1	1
Scen. II (25% sales aff.)			4	3	2
Scen. III (40% sales aff.)			6	4	3
Scen. IV (+VSD)			10	10	9
Scen. V (+Heat Recovery)			5	5	5

The table shows that industry revenue is not much affected by the scenario's. The highest effect is for Scenario IV (+0.2%, in 2030), the smallest effect for scenario I (+0.03% in 2030).

R&D investment

In the scenario's a number of sales are expected to be non-compliant (this is the target 'sales affected'). These non-compliant sales comprise models which can be expected to be redesigned.

The number of low pressure configurations on offer ranges from 191 for the LP_LFCR range to 2002 for the LP-ZFCRp range. If it is assumed that in general a frame size accommodates some 20-30 different configurations (pressure and flow variants and cooling variants) the number of frame sizes ranges from 7 to 80.

Table 111 LP configurations

Configurations, per pressure category (bar(a))	LP_ZFCR	LP_ZFCRp	LP_LFCR	LP_WFCR
1.1	504	466	28	177
1.3	775	1177	75	663
1.5	192	260	56	258
1.8	24	30	1	50
2.2	26	43	7	6
2.6	7	1	0	2
3.1	12	11	5	9
3.6	2	14	3	3
4.2	0	0	16	0
total	1542	2002	191	1168
frame sizes	~60	~80	~7	~50

For the oil-free range the number of configurations per frame size is probably lower, as more equipment is made bespoke, and two categories are already split over the cooling method. Assuming 10 configurations per frame size results in 5 to 14 frame sizes

Table 112 OF configurations

Configurations	OF_ZFCR|A	OF_ZFCR|W	OF_LFCR	OF_WFCR|A	OF_WFCR|W
bar(a) 5.0	4	0	6	0	1
6.1	53	32	1	14	17
7.2	63	40	35	17	14
8.3	12	7	15	11	16
9.4	6	7	8	3	5
10.6		1	4		
11.7			1		
12.8					
13.9					
total	138	87	70	45	53
frame sizes	14	9	7	5	5

If it is assumed that the average ***overlap*** of adjacent frame sizes is 25%, the redesign effort (share of models to redesign) can be calculated.

The ***redesign effort*** exceeds that of the 'sales affected', as several of the surviving models of each frame size will also need to be partially redesigned to yield a consistent coverage of its power range. The number of affected frame sizes is calculated as:

affected frame sizes = affected sales + (overlap * affected sales)*2 [overlap goes in two directions]

The redesign effort can then be calculated as:

redesign effort = affected frame sizes / design cycle

For the three sales affected targets the effort is calculated as:

Table 113 Calculation redesign effort

	Unit	Calculation		
target sales affected	% sales	10% (Scen.I)	25% (Scen.II)	40% (Scen.III)
affected frame sizes	% frame sizes	15%	37.5%	60%
design cycle	years	10	10	10
redesign effort	years	1.5	3.8	6

The financial implications are assessed as follows:

- manufacturers in the mechanical industry typically spend 2 to 3% of their revenues to R&D [203];
- The total combined turnover of the compressor industry is 989 million EUR (this covers purchase, installation and servicing, year 2015) [204];
- The total expected R&D costs is therefore some 30 million EUR per year;

[203] Source: VDMA Maschinenbau in Zahl und Bild 2014, see: http://ost.vdma.org/en/article/-/articleview/1961100

[204] Source: tables on purchase costs, installation costs and servicing costs

- Therefore the cost to manufacturers, not including costs (investments) in production infrastructure, is:
  - if target is 10% 'sales affected': 45 million;
  - if target is 25% 'sales affected': 114 million;
  - if target is 40% 'sales affected': 180 million;

No impacts on R&D have been calculated for the scenario's "VSD" and "Heat Recovery".

Production investment

Manufacturers have stated that the phase-out of models and their replacement by compliant models will require substantial investment in the production apparatus.

- Various machine tools will need to cope with more variants of the compressor stages, also increasing the logistics and the layout of production lines.
- It is estimated that if 40% of models are banned some 2 additional compressor production stages will be necessary.
- To manufacture in a competitive set-up, at least 1 extra rotor machining line may be acquired, consisting of a lathe, a shaft grinding machine, and a profile roughing and grinding machine, representing a typical capital expenditure of 2 million EUR per manufacturer.
- Moreover casting moulds and machine fixtures will be needed for the serial production of the different components of new compressor stages, which may add up to 1 million EUR per manufacturer.
- Investments in the new layout of the manufacturing lines of the new compressor packages can be estimated at a cost of 1 million EUR per manufacturer.

Total investments therefore amount to approximately 4 million EUR per manufacturer (at 40% sales affected), or some 40 million EUR for the main compressor manufacturers active in Europe. For 10% and 25% sales affected the extra production costs are assessed at 10 and 25 million respectively. For the VSD-option and Heat Recovery-option, additional production costs are assumed zero.

In addition there may be divestment of existing production tools which have become obsolete, and need to be written-off at once, estimated at 1 million EUR per manufacturer, or some 10 million EUR for all manufacturers combined.

As many EU manufacturers are also exporting, the obsolete production lines may also be converted to "export-only" products. The disinvestment is ignored.

Testing costs

Due to the introduction of requirements one can expect an increase of audit testing. A certain percentage of serial production machines will undergo additional data testing in a separate test facility under controlled environment. It is estimated that typically 10% of the machines in series production annually put on the EU market need to pass an audit test for a systematic verification of compliancy with eco-design measures.

The typical cost of a test cell, including qualified personnel and energy, is estimated to be some 400 euro/hour (minimum 300 euro/hour and maximum 500 euro/hour, as a range over the complete power range of standard air compressors). The average test duration for mounting on the test bench, connecting pipes, ducts and instrumentation, stabilizing and measuring is approximately 3 hours per test, or 1500 EUR for a single test.

The 3 to 9 test points required for calculating the average efficiency should not pose too much problems for testers. There is no need for additional instrumentation or equipment. Variable flow equipment is already tested at a minimum of 5 working points (in accordance with Annex E of ISO 1217:2009) at a single discharge pressure. The test duration will probably increase though, putting some pressure on the availability of test facilities.

Considering the extra audit tests to be performed (to ensure all equipment is compliant), a need for additional data testing capacity equivalent to 3 to 4 test facilities may arise. The cost for a test facility can be estimated at around 0.5 to 1.5 Million euro/cell in average for a company in EU-28, which means an additional total investment of ca. 2 to 6 Million euro (depending on the range to be tested this can be less or more). In this study an average of 4 million is assumed, which applies to all scenario's as the provision of mandatory, harmonized, information is required for all scenario's.

The additional investment is then calculated as follows:

Table 114 Additional costs related to R&D, production and testing

Extra costs (million EUR)	R&D	Production	Testing	Total
Scen. I (10% sales aff.)	45	10	4	59
Scen. II (25% sales aff.)	114	25	4	143
Scen. III (40% sales aff.)	180	40	4	224
Scen. IV (+VSD)	PM	PM	4	4 +PM
Scen. V (+Heat Recovery)	PM	PM	4	4 +PM

PM = pro memori, or could not be quantified.

7.5.2 Customer impacts

Customer impacts are expressed as acquisition costs (purchase + installation), operating costs (maintenance + energy) and total expenditure (acquisition and operating costs combined).

Acquisition costs

Total acquisition costs are some 535 million EUR in 2015, climbing to 590 million EUR in 2015 for the BAU scenario. The other scenario's increase the acquisition costs by 0.13% (Scenario I) to 1.6% (scenario IV). The costs are almost evenly split (51/49) over the Low pressure and Oil-free application ranges.

Figure 82 Acquisition costs (purchase + installation) 1990-2050

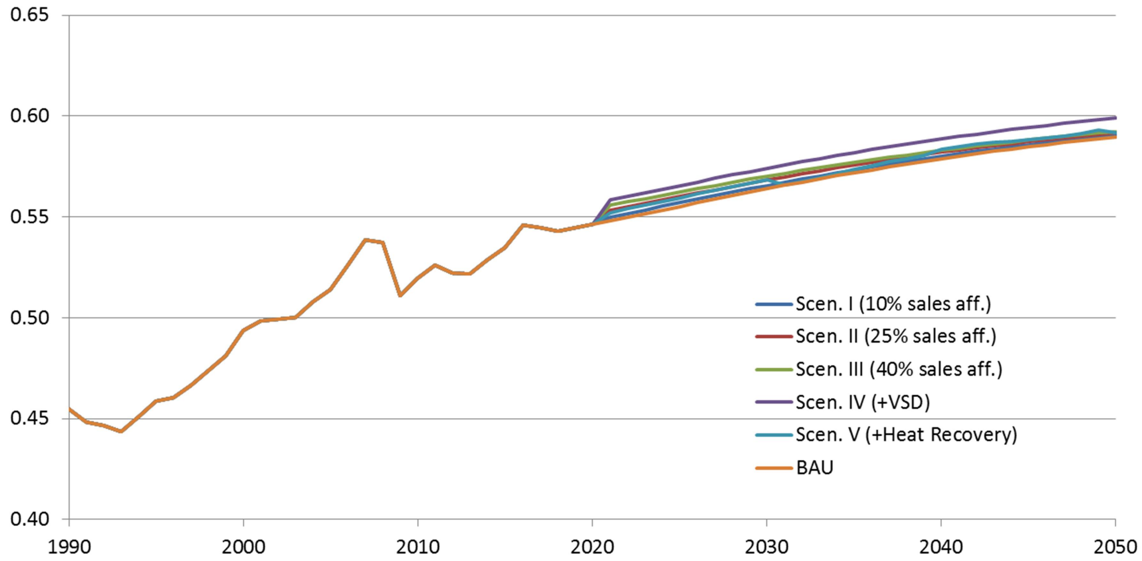
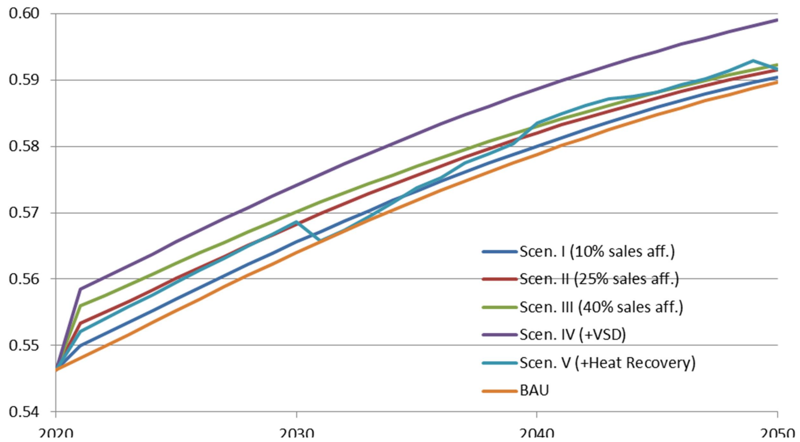
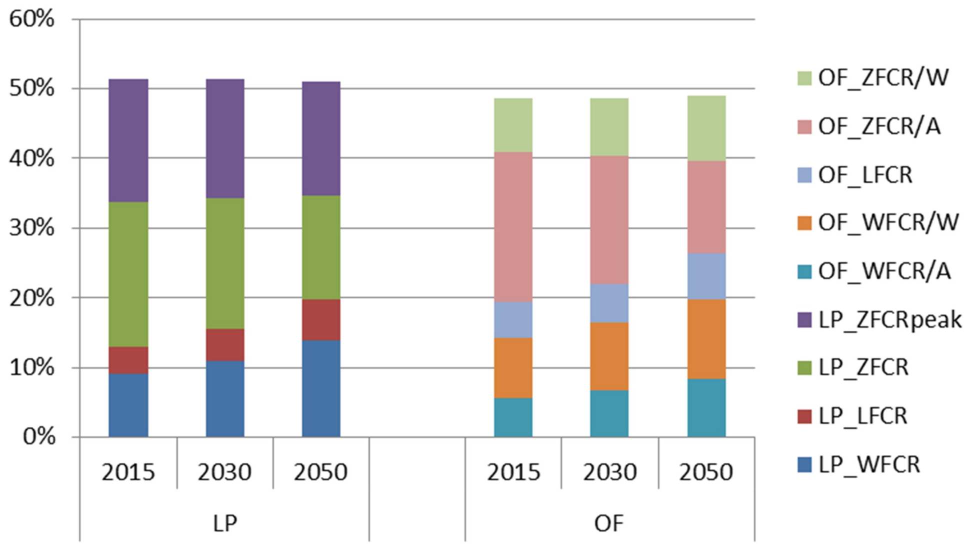


Figure 83 Detail of acquisition costs (purchase + installation) 2020-2050



The staggered (light blue) curve calculated for Scenario V Heat Recovery is due to 1) that the calculation model uses a ramp-up time of 10 years, so after ten years the investment in heat recovery is assumed to be limited to replacement only, and 2) the fact that the relative size and average product life of the various flow categories is different which means that replacement costs are spread over different periods and different levels.

Figure 84 Detail of acquisition costs (share of total) by category



The costs and differences compared to BAU of the various scenarios, are shown below.

Table 115 Acquisition costs

Acquisition costs (billion EUR)	2015	2020	2030	2040	2050
Scen. I (10% sales aff.)	0.535	0.546	0.566	0.580	0.590
Scen. II (25% sales aff.)	0.535	0.546	0.568	0.582	0.592
Scen. III (40% sales aff.)	0.535	0.546	0.570	0.583	0.592
Scen. IV (+VSD)	0.535	0.546	0.574	0.589	0.599
Scen. V (+Heat Recovery)	0.535	0.546	0.569	0.584	0.592
BAU	0.535	0.546	0.564	0.579	0.590
Difference to BAU (million EUR)					
Scen. I (10% sales aff.)			1.6	1.3	0.8

Scen. II (25% sales aff.)	4.3	3.3	1.9
Scen. III (40% sales aff.)	6.2	4.2	2.6
Scen. IV (+VSD)	10.2	9.8	9.4
Scen. V (+Heat Recovery)	4.6	4.8	2.0

Operating costs

Total operating costs (energy and maintenance, including refurbishment) are some 7859 million EUR in 2015, climbing to 21330 million EUR in 2015 for the BAU scenario. The other scenario's reduce the operating costs by minus 0.16% (Scenario I) to minus 6.1% (scenario IV). The costs are almost split as 41 to 59 for the Low pressure and Oil-free application ranges respectively (2015).

Figure 85 Operating costs

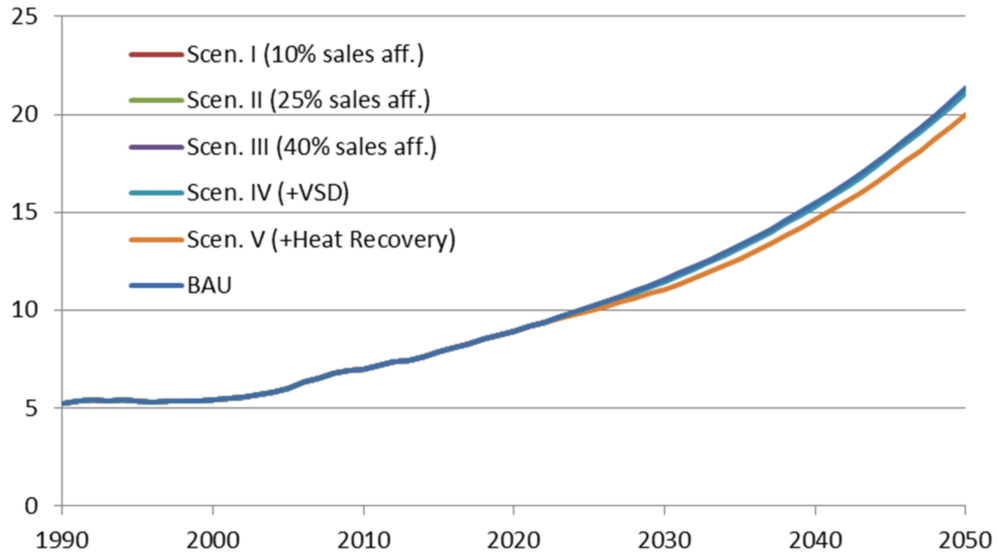


Table 116 Operating costs

Operating costs (in bn €)	2015	2020	2030	2040	2050
Scen. I (10% sales aff.)	7.9	8.9	11.6	15.4	21.3
Scen. II (25% sales aff.)	7.9	8.9	11.5	15.4	21.2
Scen. III (40% sales aff.)	7.9	8.9	11.5	15.3	21.2
Scen. IV (+VSD)	7.9	8.9	11.5	15.3	21.1
Scen. V (+Heat Recovery)	7.9	8.9	11.1	14.6	20.0
BAU	7.9	8.9	11.6	15.4	21.3
Difference to BAU (million EUR)					
Scen. I (10% sales aff.)			-19	-29	-34
Scen. II (25% sales aff.)			-54	-86	-88
Scen. III (40% sales aff.)			-78	-115	-113
Scen. IV (+VSD)			-106	-152	-216
Scen. V (+Heat Recovery)			-489	-846	-1311

Total expenditure

Figure 86 Expenditure (all annual costs)

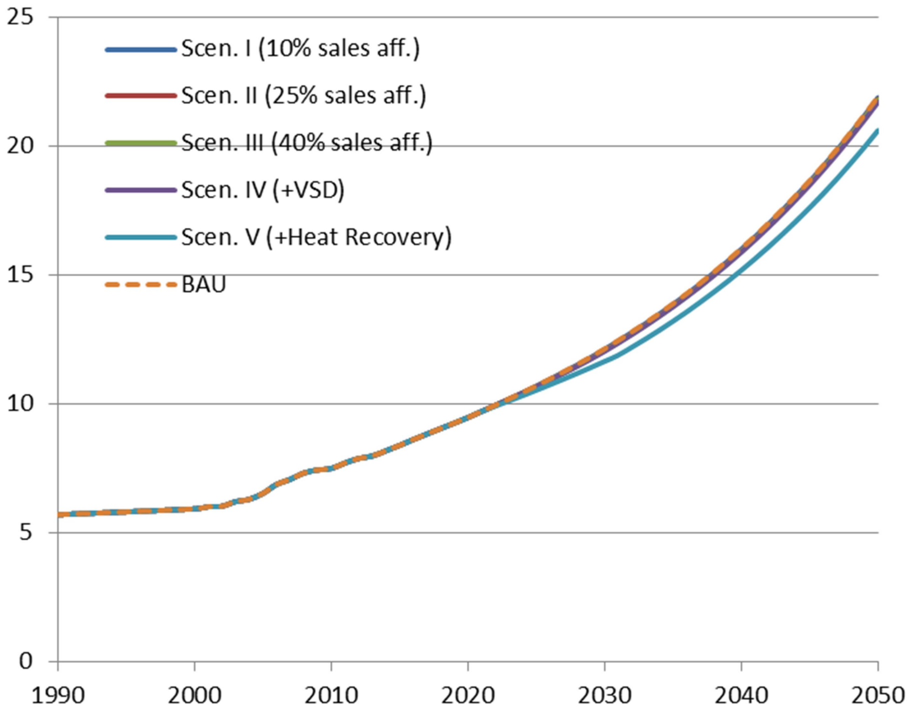
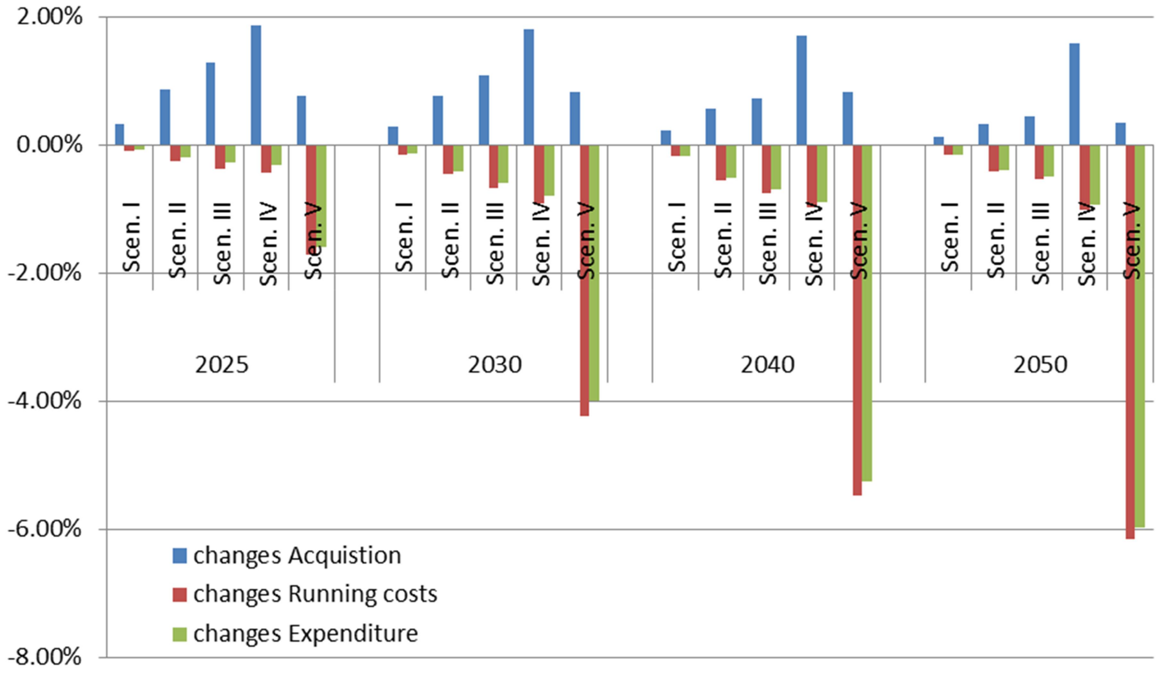


Table 117 Total expenditure

Expenditure (in billion EUR)	2015	2020	2030	2040	2050
Scen. I (10% sales aff.)	8.4	9.5	12.1	16.0	21.9
Scen. II (25% sales aff.)	8.4	9.5	12.1	15.9	21.8
Scen. III (40% sales aff.)	8.4	9.5	12.1	15.9	21.8
Scen. IV (+VSD)	8.4	9.5	12.0	15.9	21.7
Scen. V (+Heat Recovery)	8.4	9.5	11.7	15.2	20.6
BAU	8.4	9.5	12.1	16.0	21.9
Difference to BAU (million EUR)					
Scen. I (10% sales aff.)			-17	-27	-33
Scen. II (25% sales aff.)			-49	-83	-86
Scen. III (40% sales aff.)			-72	-111	-110
Scen. IV (+VSD)			-95	-142	-207
Scen. V (+Heat Recovery)			-485	-841	-1309
Scen. I (10% sales aff.)			-0.1%	-0.2%	-0.2%
Scen. II (25% sales aff.)			-0.4%	-0.5%	-0.4%
Scen. III (40% sales aff.)			-0.6%	-0.7%	-0.5%
Scen. IV (+VSD)			-0.8%	-0.9%	-0.9%
Scen. V (+Heat Recovery)			-4.0%	-5.2%	-6.0%

Figure 87 Changes in total expenditure and cost components (% reduced / increased)



The calculations show that all scenario's result in lower expenditure, but the reductions are very small.

The heat recovery scenario (assuming an uptake of heat recovery applications up to 20% of the overall stock) results in the highest savings of 6% in 2050. Note that the investment costs represent modifications to the compressor package only, and not the remainder of the recovery system.

7.5.3 Sensitivity analysis main impacts

Changes in electricity escalation rate

When setting the escalation rate of electricity to zero (meaning no further price increase from 2014 onwards) the total expenditure is reduced by more than 50% in 2050 when compared to the '4% escalation rate' calculations. The share of electricity costs remains constant at close to 40% of the operating costs.

The differences between scenario's and the monetary savings are also reduced.

Table 118 Expenditure at zero % escalation rate for electricity

Expenditure (in bn €)	2015	2020	2030	2040	2050
Scen. I (10% sales aff.)	8.2	8.5	9.0	9.4	9.8
Scen. II (25% sales aff.)	8.2	8.5	9.0	9.4	9.8
Scen. III (40% sales aff.)	8.2	8.5	9.0	9.4	9.8
Scen. IV (+VSD)	8.2	8.5	9.0	9.4	9.8
Scen. V (+Heat Recovery)	8.2	8.5	8.8	9.2	9.5
BAU	8.2	8.5	9.0	9.4	9.8
Difference to BAU (million EUR)					
Scen. I (10% sales aff.)			-8	-9	-7
Scen. II (25% sales aff.)			-23	-27	-19
Scen. III (40% sales aff.)			-34	-36	-24
Scen. IV (+VSD)			-44	-43	-41

Scen. V (+Heat Recovery)	-247	-289	-305
Scen. I (10% sales aff.)	-0.1%	-0.1%	-0.1%
Scen. II (25% sales aff.)	-0.3%	-0.3%	-0.2%
Scen. III (40% sales aff.)	-0.4%	-0.4%	-0.2%
Scen. IV (+VSD)	-0.5%	-0.5%	-0.4%
Scen. V (+Heat Recovery)	-2.7%	-3.1%	-3.1%

Figure 88 Expenditure at zero % escalation rate

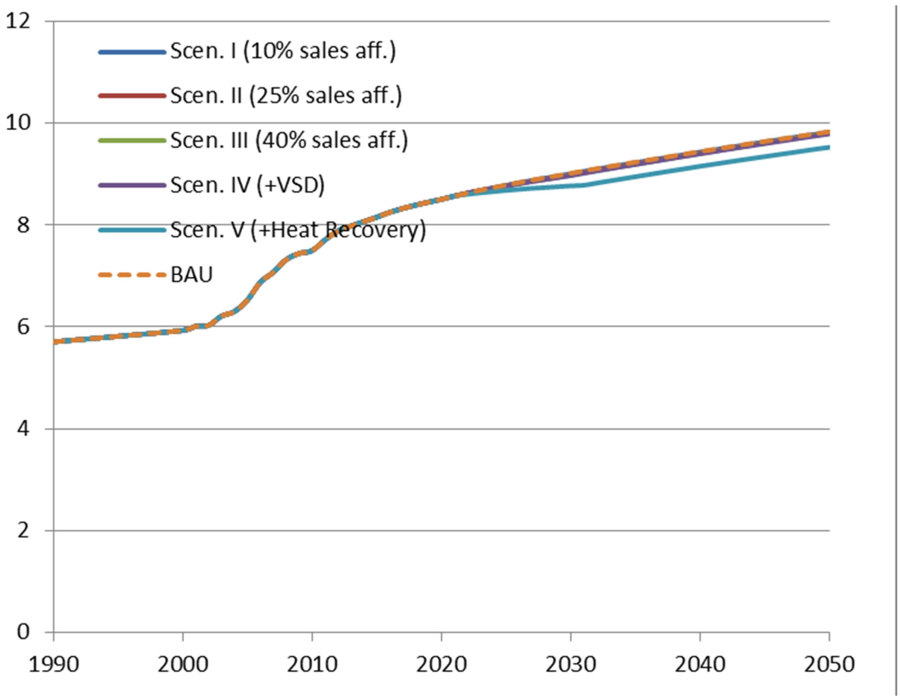
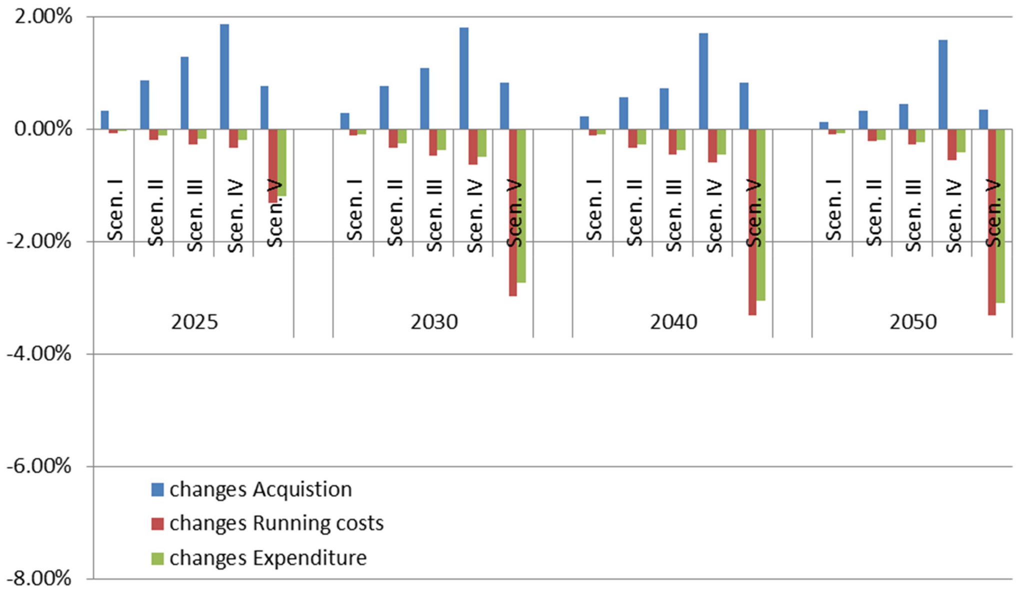


Figure 89 Changes in total expenditure and cost components (% reduced / increased) at zero % escalation rate



Changes in purchase price

This analysis describes the effect of an increase of price elasticity with efficiency. To achieve this the factor b2 (as described in Task 2, section 2.5.1) is increased by a factor 1.1. This results in a varying price increase as the price is also dependent on the size of the equipment (kW) and the other factors (notably a low factor 'b1' will soften the effects of the increase in 'b2'). The table below shows the results for the average appliances in their flow categories.

Table 119 Changes in prices due to change in factor 'b2'

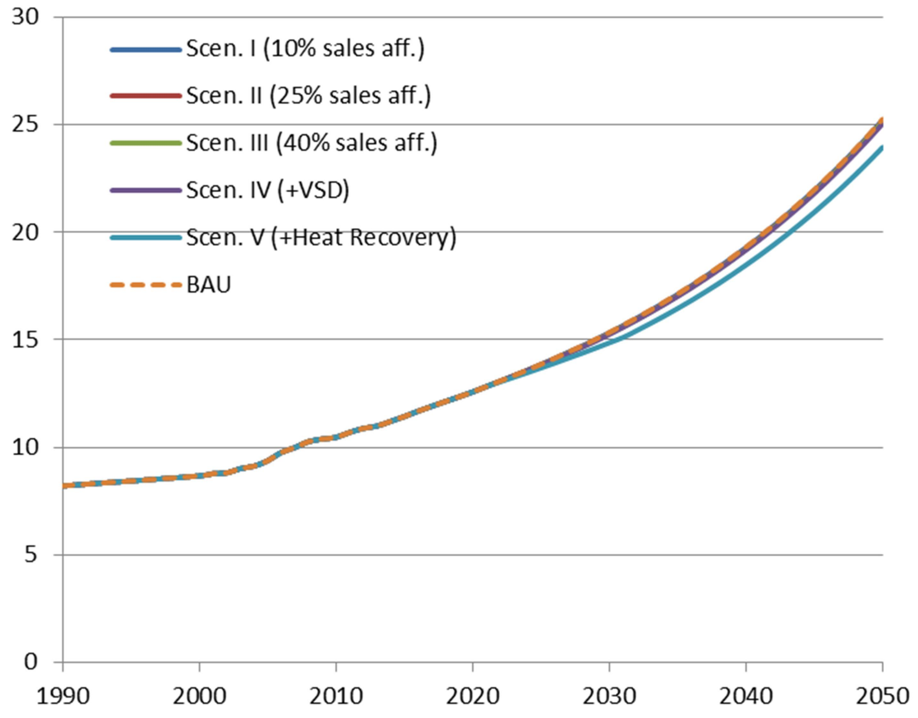
Flow category	Avg.power input	Avg. efficiency	'New' Street price	former street price	Difference	Change (%)
LP_WFCR	29.4	56.0%	€25,138	€15,634	€9,504	161%
LP_LFCR	58.4	67.7%	€51,848	€33,816	€18,032	153%
LP_ZFCR	8.9	38.2%	€11,021	€7,230	€3,791	152%
LP_ZFCRP	23.5	51.7%	€24,494	€16,563	€7,931	148%
OF_WFCR|A	26.3	55.3%	€29,721	€26,686	€3,035	111%
OF_WFCR|W	162.3	66.4%	€85,704	€78,899	€6,805	109%
OF_LFCR	185.0	64.3%	€185,242	€90,152	€95,091	205%
OF_ZFCR|A	13.7	52.6%	€29,919	€16,637	€13,281	180%
OF_ZFCR|W	80.4	69.3%	€89,378	€46,128	€43,250	194%

Table 120 Expenditure for 'b2' is increased by 1.1

Expenditure (in bn €)	2015	2020	2030	2040	2050
Scen. I (10% sales aff.)	11.4	12.6	15.3	19.3	25.2
Scen. II (25% sales aff.)	11.4	12.6	15.3	19.2	25.2
Scen. III (40% sales aff.)	11.4	12.6	15.3	19.2	25.2
Scen. IV (+VSD)	11.4	12.6	15.2	19.2	25.1
Scen. V (+Heat Recovery)	11.4	12.6	14.9	18.5	24.0
BAU	11.4	12.6	15.3	19.3	25.3
Difference to BAU (million EUR)					
Scen. I (10% sales aff.)			-16	-26	-33
Scen. II (25% sales aff.)			-45	-79	-84
Scen. III (40% sales aff.)			-65	-107	-108
Scen. IV (+VSD)			-95	-142	-207
Scen. V (+Heat Recovery)			-482	-838	-1308
Scen. I (10% sales aff.)			-0.1%	-0.1%	-0.1%
Scen. II (25% sales aff.)			-0.3%	-0.4%	-0.3%
Scen. III (40% sales aff.)			-0.4%	-0.6%	-0.4%
Scen. IV (+VSD)			-0.6%	-0.7%	-0.8%
Scen. V (+Heat Recovery)			-3.1%	-4.3%	-5.2%

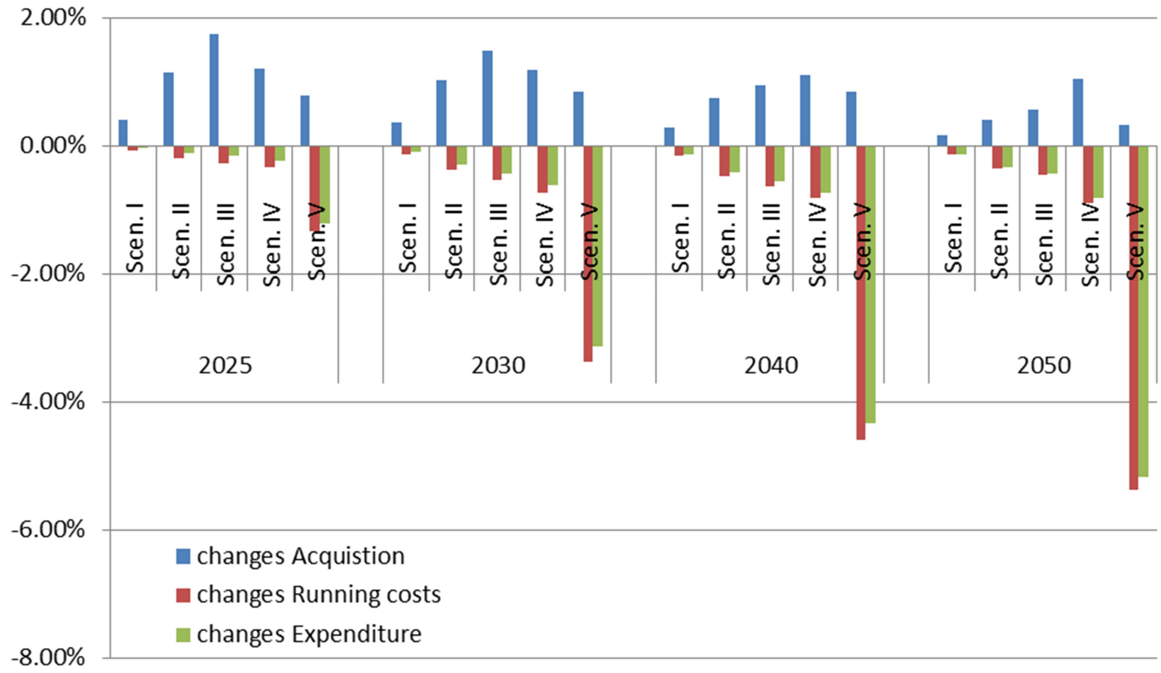
The maximum savings have reduced, but only slightly due to the strong dependency of the expenditure on the electricity costs.

Figure 90 Expenditure for 'b2' is increased by 1.1



The overall, absolute, expenditure has of course increased compared to the reference scenario.

Figure 91 Changes in total expenditure and cost components (% reduced / increased) for 'b2' is increased by 1.1



The overall expenditure of the scenario's is still below that of the BAU scenario, but the savings are typically below 1%.

A scenario closer to BAT

This scenario describes the effect of implementing measures that are closer to the Best Available Technology mark. It has been assessed by defining D-values in three tiers that result in a share of affected sales of 80%, 90% and 95%, before correction with BAU improvement. This latter approach is necessary as consideration of the BAU improvement for target setting (95% of sales affected) for certain flow categories would lead to initial sales affected percentages of >100% (meaning no products left on the market).

Table 121 D-values for the 'new' BAT scenario's

Scen. I (BAT eff.)	D-value, Tier-1	D-value, Tier-2	D-value, Tier-3
LP_WFCR	7	12	16
LP_LFCR	5	8	10
LP_ZFCR	3	8	12
LP_ZFCRpeak	3	6	8
OF_WFCR/A	6	10	13
OF_WFCR/W	5	9	13
OF_LFCR	6	12	18
OF_ZFCR/A	2	5	7
OF_ZFCR/W	7	12	16
Scen. II (BAT eff.+VSD.)			
LP_WFCR	7	12	16
LP_LFCR	5	8	10
LP_ZFCR	3	8	12
LP_ZFCRpeak	3	6	8
OF_WFCR/A	6	10	13
OF_WFCR/W	5	9	13
OF_LFCR	6	12	18
OF_ZFCR/A	2	5	7
OF_ZFCR/W	7	12	16
Scen. III (BAT eff. +VSD +HR)			
LP_WFCR	7	12	16
LP_LFCR	5	8	10
LP_ZFCR	3	8	12
LP_ZFCRpeak	3	6	8
OF_WFCR/A	6	10	13
OF_WFCR/W	5	9	13
OF_LFCR	6	12	18
OF_ZFCR/A	2	5	7
OF_ZFCR/W	7	12	16

In addition this scenario was combined with the VSD scenario defined before and with the VSD scenario + the heat recovery scenario, resulting in three additional scenario's with BAT efficiency as common element. The three tiers for minimum efficiency requirements have been modelled to come into effect in 2021, 2024 and 2027. The VSD and heat recovery savings start at year 2021.

For reference the former scenario IV (VSD only) and V (heat recovery only) have been included for reference only in the below figure and table.

Figure 92 Energy consumption for BAT scenario's

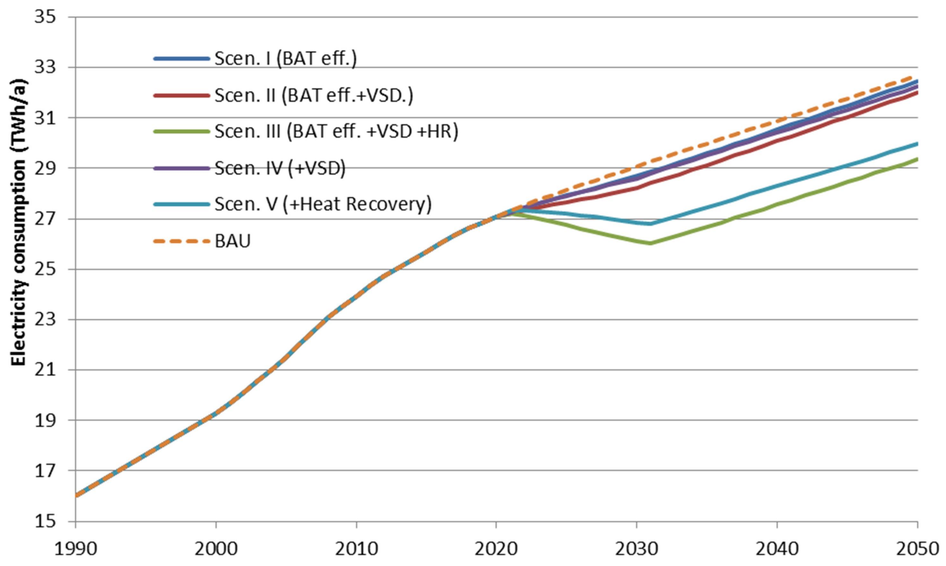


Table 122 Energy savings for BAT scenario's

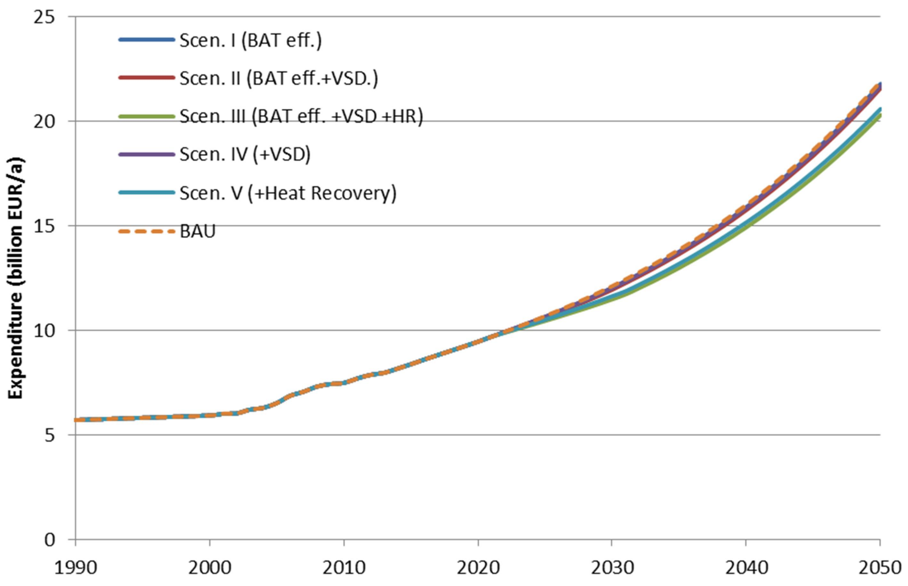
Electricity saved (TWh/a)	2030	2040	2050
Scen. I (BAT eff.)	0.37	0.35	0.23
Scen. II (BAT eff.+VSD.)	0.85	0.81	0.67
Scen. III (BAT eff. +VSD +HR)	2.96	3.33	3.32
Scen. IV (+VSD)	0.48	0.46	0.45
Scen. V (+Heat Recovery)	2.22	2.59	2.71

The assessment shows that the additional savings of the BAT efficiency only scenario (new Scenario I) are relatively modest (some 0.37, against 0.35 TWh/a savings for the original scenario III (40% sales affected).

The overall expenditure is still below the BAU expenditure, meaning that costs can be recuperated over the product life.

It must be said that this analysis cannot compute the availability of products in certain flow/pressure classes. Therefore it cannot guarantee that there is an adequately sized product on the market available for anyone. With 'sales affected' reaching percentages of 80% and higher, it is considered inevitable that certain products are removed from the market with no efficient alternative available. This means that customers have to look for (combinations of) other products to meet their air demands, which could lead to oversizing (the new product is too large for its application) or to purchasing two smaller machines. This effect and its impacts could not be quantified.

Figure 93 Expenditure for BAT scenario's



Representativeness of the sales data

As stated in Task 3 and 4, the values for LP and OF sales originate from a manufacturer survey (data collection) organised in the context of this study, during the summer of 2016.

The participants to this data collection are the main manufacturers active in the EU, and comprise both domestic producers as producers from outside the EU. Some 9 manufacturers contributed to LP data and 7 manufacturers contributed to OF data. Most of these manufacturers own several 'brands" and sales data was not limited to the main brand name only.

When looking at the list of manufacturers of equipment provided in section 2.4.1, the total number of manufacturers of equipment appears much higher, it is not known whether and to what degree these other manufacturers are active in the EU.

Supposing that the total number of manufacturers active in the EU is indeed higher than the number of manufacturers that actually participated in the survey, in what way would their inclusion have affected the conclusions (regarding sales, and overall energy consumption)?

Most of the manufacturers that did not participate are probably active in the low pressure application range (as the oil-free range is covered by a few manufacturers only and those relevant for the EU did participate) and more particularly in the low-cost market.

These are generally products with low power consumption in the LP_ZFCR category, such as regenerative blowers. The current assessment shows that the LP_ZFCR category makes up 60% of the overall LP sales, but represent only 33% of the installed capacity (and also approximately 33% of the electricity consumption of LP range) in 2015.

If these sales would be double (not 13638 per year but 27276 in 2015) the share in sales would increase from 60% to 75% and the capacity placed on the market (MW) from 33% to 50% for the LP range. The overall electricity consumption would increase from 10 TWh to 13 TWh in 2015 for the LP range. On the total electricity consumption of 26 TWh this is an increase of 11%.

The savings, assuming doubled LP_ZFCR sales, for this revised scenario I, II and III are between 0.03 TWh/a in 2030 to 0.10 TWh/a, or 0.1 to 0.3% of the originally calculated energy consumption of 29 TWh for 2030.

Given the overall uncertainties in the assessment this margin is considered acceptable.

7.6 Conclusion & recommendations

In this section the analyses of the previous Tasks are summarized and recommendations for future policies and measures are made.

7.6.1 Conclusion

The Task 1 analysis shows that the product performance data needed to calculate energy efficiency can be established using two distinct product standards, one for each main technology i.e. positive displacement and dynamic compressor packages. Although products belonging to either of these main technologies may compete for the same application in the marketplace, establishing the performances using these two standards is not aligned and makes comparing performances across technologies difficult. This situation does not help customers to easily recognise the more efficient products.

Attempts are being made by standardization organizations to improve this situation, but these processes are slow and depend on consensus, which can be hard to reach in a market where various technologies are competing head on. As the purpose of Ecodesign legislation is to harmonize the European market with regard to environmental aspects of products, the low pressure and oil-free market present a case where further harmonization of product performance standards could correct this market failure.

Currently no specific measures for low pressure and oil-free compressor packages exist in or outside the EU. Voluntary agreements have not been proposed by the relevant industries.

The market analysis (Task 2) and environmental analysis (Task 5, based on Task 2 and 3) show that although the market significance of the product group is limited, the environmental significance is not. The overall sales are assessed at slightly less than 32 000 units in 2015. The combined electricity consumption of the products is assessed at 26 TWh in year 2015, and is expected to increase to 32 TWh in 2050 if no measures are introduced and current trends continue. The combined electricity consumption corresponds to approximately 1% of the total EU 28 electricity consumption in 2015.

The technical analysis (Task 4) shows that although there is disparity in energy efficiency over the whole range of available products, most products are fairly similar in performance. This means that relatively small changes in minimum energy efficiency lead to relatively large changes in share of products affected by the minium requirement (as shown in section 7.3.2). Other options for achieving energy savings (Task 6) are application of heat recovery and better controls for single speed machines in variable flow/pressure applications by using VSD.

In Task 7 it has been calculated that a measure aimed at improving package efficiency , affecting some 40% of the models (on the market in 2015), would result in energy savings close to 0.35 TWh in 2040. This is equivalent to 1% saving of the total energy consumption of the products.

Increased uptake of VSD equipment, quantified as 50% of units in stock being capable of variable flow by 2031 (start date 2021 plus 10 years ramp-up)[205], results in 0.5 TWh electricity savings in 2040. This is equivalent to 1.5% saving of the total energy consumption of the products.

Increased uptake of heat recovery, quantified as a 20% increase of heat recovery by units in stock, results in savings equivalent to 2.6 TWh electricity in 2040, which is a saving of approximately 8% of the total electricity consumption of these products.

Contrary to minimum energy efficiency requirements, the savings calculated for VSD and heat recovery scenarios cannot be unlocked by Ecodesign measures alone. Both require an awareness raising campaign to make customers and others involved in compressed air systems (auditors, local authorities issuing permits, etc.) more aware of possible savings. This campaign could be modelled on the example of the US 'Compressed Air Challenge'. In order to lower

[205] The Business-as-usual scenario (BAU) assumed a share of variable flow equipment (% of total stock, in units) of 34% in 2015, increasing to 38% in 2030, 42% in 2040 and 47% in 2050.

possible thresholds for heat recovery in specific equipment some technical requirements can be made mandatory.

As regards resource efficiency, the policies for low pressure and oil-free compressor packages should be aligned to policies for other products in the motor driven system group, such as electric motors, fans and pumps.

7.6.2 Policy recommendations[206]

The recommendations for policies and measures are:

1. To introduce an ecodesign regulation requiring the (mandatory) provision of **product information sheets**, presenting the main performance parameters, to be established using (harmonised) standards, based on common reference conditions. The sheets would allow easier comparison of performances of products when placed on the market, even if the main technologies are different and different product standards have been used to assess the performances. This measure does require further work on the standards to be used for performance assessment.

   In addition to information requirements, the proposed Ecodesign regulation can:

   i) require resource efficiency information to be provided, preferably harmonised with information requirements for similar product groups such as electric motors, fans and pumps. The information may already be present on parts or components of the product, e.g. indicating presence of critical raw materials in motors. If usable standards exist, specific product requirements related to end-of-life treatment may be introduced (in analogy to the WEEE Directive, requiring easy disassembly of displays and/or circuit boards, etc.).

   ii) introduce specific (design) requirements to make sure that recovery of heat can take place and is not obstructed. The requirements may relate to the presence of parts or product characteristics that facilitate connecting to systems requiring heat, besides the water-cooling system itself (where relevant). The study suggests openings in the sound canopy, presence of (3-way) valves, etc.

   iii) introduce minimum energy efficiency requirements, removing the worst performers from the market. The stringency of requirements needs to be balanced with the impacts on industry and customers, requiring further consultation.

   Stakeholders have argued that the risk for the EU becoming a dumping ground for oil-free products with poor energy efficiency is considered to be fairly low as, contrary to the 'standard air' package market, only a limited number of manufacturers produces oil-free (rotary or turbo) air-ends. And now that the US DoE appears to abstain from rulemaking for low pressure and oil-free compressor packages in the US, and focuses on lubricated packages only (status February 2017), this risk is further minimised. Stakeholders have repeated that proper market surveillance remains to be an important element for an effective regulation, for 'low pressure' products in particular.

2. The second recommendation is to introduce an European Compressed Air initiative, comparable to the Compressed Air Challenge in the Unites States. The initiative is set up as a voluntary collaboration of industrial users, manufacturers, distributors and their associations, consultants, research and development agencies, energy efficiency organizations and utilities.

   The initiative promotes energy and operational efficiency in compressed air systems for industry through information and training, leading end users to adopt efficient practices and technologies and seek cooperation among key stakeholders, following regulations to that purpose..

[206] These recommendations are in no way to be perceived as the opinion of the European Commission (disclaimer applies)

In doing so, the initiative is expected to contribute to the roll out of variable flow equipment where recommendable. Furthermore it is expected to help customers in deciding for heat recovery (for instance by presenting tools to easily calculate costs and savings, plus providing technical guidance).

This European initiative cannot be realised under the Ecodesign or Energy Labelling Directive, but it may be created in a way similar to the EU BUILD UP initiative[207] and the European Motor Challenge Program[208]. Another example is the 'Come On labels' initiative[209], also supported by Intelligent Energy Europe, the goal of which was to enhance the visibility and credibility of the EU energy label.

As recommendation #1 introduces mandatory information requirements for low pressure and oil-free compressors, one can argue that there will be a need for collecting and spreading information and best practices related to legislation, equipment testing, compliance monitoring, promotion, and general technical guidance, etc.

3. Energy Labelling is not recommended as the low pressure market and oil-free market are predominantly a business-to-business market where product characteristics are selected or specified by customers, and manufacturers then proceed to manufacture the product (using many standardized components). Furthermore, there would be a large overlap with the product information sheets required under recommendation #1.

Recommendation #1 for an Ecodesign regulation (introducing information requirements) and recommendation #2 for an information campaign are expected to strengthen each other as the regulation gives 'weight' to the significance of energy saving in this product group and helps to harmonize product information to be disseminated in the context of the information campaign.

---

[207] The BUILD UP initiative, part of Intelligent Energy Europe, was created to support Member States in the implementation of the EPBD (http://www.buildup.eu/en/about-portal)

[208] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/european-motor-challenge-programme-evaluation-2003-2009 (and follow-up: http://ec.europa.eu/energy/intelligent/projects/en/projects/dexa-mcp)

[209] See: http://www.come-on-labels.eu/about-the-project/project-summary-eu

ANNEX A: Sold production, exports and imports by PRODCOM / Units

Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data (DS_066341)

Url: http://ec.europa.eu/eurostat/web/prodcom/data/database

In Units (pieces)

Table 123 Sold production, exports and imports by PRODCOM / Units

	Production	Import	Export	Apparent consumption
28132530 - Turbo-compressors, single stage				
2005	7.181.710	840.709	1.443.062	6.579.357
2006	7.763.613	637.244	1.734.243	6.666.614
2007	8.338.671	814.357	2.025.704	7.127.324
2008	6.987.883	1.217.667	2.443.875	5.761.675
2009	5.859.952	849.511	1.354.634	5.354.829
2010	7.553.969	2.354.773	1.740.946	8.167.796
2011	9.344.084	2.695.972	1.883.617	10.156.439
2012	9.722.880	2.549.236	1.690.417	10.581.699
2013	10.190.486	2.315.057	1.579.442	10.926.101
2014	10.632.361	1.656.120	1.840.836	10.447.645
28132550 - Turbo-compressors, multistage				
2005	884	29.115	12.451	17.548
2006	2.531	122.975	20.003	105.503
2007	1.400	252.333	36.676	217.057
2008	1.200	417.320	52.433	366.087
2009	1.134	457.129	49.084	409.179
2010	1.128	1.270.206	507.997	763.337
2011	1.600	1.426.879	654.065	774.414
2012	2.000	1.267.885	147.054	1.122.831
2013	30.000	1.182.947	145.657	1.067.290
2014	100.000	936.349	178.102	858.247
28132630 - Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow <= 60 m³/hour				
2005	1.500.000	2.031.483	498.057	3.033.426
2006	1.000.000	1.726.494	578.377	2.148.117
2007	1.500.000	2.389.410	627.107	3.262.303
2008	1.500.000	2.518.949	714.379	3.304.570
2009	1.500.000	2.810.827	703.616	3.607.211
2010	1.200.000	5.607.808	873.878	5.933.930
2011	2.400.000	7.253.245	968.326	8.684.919

2012	1.500.000	6.887.911	985.348	7.402.563
2013	1.200.000	7.235.640	1.057.925	7.377.715
2014	1.104.598	9.612.420	1.295.462	9.421.556

28132650 - Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow per hour > 60 m³				
2005	22.940	23.377	4.290	42.027
2006	27.700	192.309	161.743	58.266
2007	33.617	118.629	48.300	103.946
2008	19.089	36.135	18.776	36.448
2009	13.310	84.097	25.960	71.447
2010	11.321	121.654	27.891	105.084
2011	11.641	95.358	40.236	66.763
2012	10.150	86.235	23.625	72.760
2013	8.999	124.689	29.213	104.475
2014	9.870	133.259	15.188	127.941

28132670 - Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour <= 120 m³				
2005	30.000	349.622	143.892	235.730
2006	230.245	171.565	233.670	168.140
2007	720.000	134.523	206.657	647.866
2008	48.955	89.666	423.468	-284.847
2009	35.000	141.025	125.811	50.214
2010	40.000	265.522	206.212	99.310
2011	47.566	408.028	184.422	271.172
2012	70.000	300.410	220.157	150.253
2013	42.222	236.988	213.752	65.458
2014	44.000	277.023	246.614	74.409

28132690 - Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour > 120 m³				
2005	3.106	6.246	4.714	4.638
2006	3.949	48.892	18.053	34.788
2007	4.558	66.008	9.878	60.688
2008	4.313	49.543	18.365	35.491
2009	4.227	37.142	16.043	25.326
2010	4.208	77.223	31.295	50.136
2011	5.124	65.523	12.986	57.661
2012	4.567	41.110	13.884	31.793
2013	3.565	49.284	9.980	42.869
2014	3.766	113.535	28.931	88.370

28132730 - Rotary displacement compressors, single-shaft				
2005	108.873	661.146	74.394	695.625
2006	100.000	513.382	92.255	521.127
2007	150.000	594.031	61.940	682.091
2008	160.000	459.496	56.714	562.782
2009	76.305	403.075	35.107	444.273
2010	80.000	651.391	86.942	644.449
2011	120.004	1.324.548	281.681	1.162.871
2012	80.001	1.438.599	139.833	1.378.767
2013	80.000	1.127.079	233.689	973.390
2014	140.000	1.782.447	461.878	1.460.569

28132753 - Multi-shaft screw compressors				
2005	180.000	5.698	118.694	67.004
2006	180.000	9.374	221.916	-32.542
2007	250.000	11.478	154.226	107.252
2008	218.578	5.831	105.705	118.704
2009	200.000	22.654	71.925	150.729
2010	210.000	23.305	113.273	120.032
2011	320.000	14.745	165.074	169.671
2012	240.000	22.518	143.960	118.558
2013	200.000	16.428	546.745	-330.317
2014	260.000	27.436	190.938	96.498

28132755 - Multi-shaft compressors (excluding screw compressors)				
2005	20.838	403.123	12.114	411.847
2006	22.150	316.836	277.468	61.518
2007	25.066	463.322	450.443	37.945
2008	25.079	536.507	42.981	518.605
2009	19.232	133.988	31.910	121.310
2010	20.000	104.398	28.054	96.344
2011	27.000	60.988	25.829	62.159
2012	18.000	22.987	21.910	19.077
2013	30.000	22.810	34.068	18.742
2014	30.000	14.519	65.633	-21.114

28132800 - Air/gas compressors excluding air/vacuum pumps used in refrigeration, air compressors mounted on wheeled chassis, turbo compressors, reciprocating and rotary displacement compressors				
2005	2.014.536	5.941.783	1.294.949	6.661.370
2006	2.000.000	7.638.307	1.320.892	8.317.415
2007	2.200.000	9.675.416	1.523.455	10.351.961
2008	2.000.000	8.850.382	1.337.950	9.512.432

2009	1.265.888	7.311.808	1.083.708	7.493.988
2010	1.200.000	7.660.730	1.582.329	7.278.401
2011	2.100.000	7.483.475	2.280.306	7.303.169
2012	2.100.000	7.422.110	2.158.281	7.363.829
2013	2.334.040	8.127.932	1.591.453	8.870.519
2014	1.792.931	8.982.502	2.175.385	8.600.048

ANNEX B: Sold production, exports and imports by PRODCOM / Value

Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data (DS_066341)
Url: http://ec.europa.eu/eurostat/web/prodcom/data/database

In value (euros)

Table 124 Sold production, exports and imports by PRODCOM / Values

	Production	Import	Export	Apparent consumption
28132530 - Turbo-compressors, single stage				
2005	1.234.225.651	185.155.160	348.537.920	1.070.842.891
2006	1.440.980.174	180.824.900	377.675.960	1.244.129.114
2007	1.540.125.290	204.013.300	481.334.870	1.262.803.720
2008	1.597.268.805	274.701.040	571.022.050	1.300.947.795
2009	1.315.914.239	246.416.540	391.152.580	1.171.178.199
2010	1.601.744.845	379.772.180	531.677.000	1.449.840.025
2011	2.060.381.430	372.388.930	603.119.900	1.829.650.460
2012	2.119.710.508	344.820.460	692.972.600	1.771.558.368
2013	2.324.778.513	390.600.930	710.973.200	2.004.406.243
2014	2.322.080.426	391.601.960	828.358.970	1.885.323.416
28132550 - Turbo-compressors, multistage				
2005	858.918.569	48.621.640	436.843.440	470.696.769
2006	590.087.915	37.849.090	391.779.540	236.157.465
2007	560.000.000	63.287.010	585.706.250	37.580.760
2008	920.000.000	82.659.470	566.608.020	436.051.450
2009	1.408.290.265	81.342.680	751.126.720	738.506.225
2010	1.439.385.686	132.239.930	864.948.720	706.676.896
2011	1.596.844.882	159.537.290	760.555.840	995.826.332
2012	1.722.456.646	132.376.700	1.176.790.410	678.042.936
2013	1.876.147.558	107.972.110	966.581.320	1.017.538.348
2014	2.200.028.762	102.613.460	985.628.940	1.317.013.282
28132630 - Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow <= 60 m³/hour				
2005	239.410.469	104.017.370	91.221.750	252.206.089
2006	151.356.790	77.804.820	102.262.910	126.898.700
2007	239.145.558	89.443.440	108.561.440	220.027.558
2008	227.930.746	114.116.870	135.210.130	206.837.486
2009	196.130.924	82.352.490	111.392.110	167.091.304
2010	232.842.110	145.696.050	136.103.570	242.434.590
2011	301.987.067	160.762.230	148.745.250	314.004.047

2012	294.091.391	159.422.490	155.773.470	297.740.411
2013	248.426.172	165.173.430	152.482.020	261.117.582
2014	244.940.123	206.048.190	144.637.030	306.351.283

28132650 - Reciprocating displacement compressors having a gauge pressure capacity <= 15 bar, giving a flow per hour > 60 m³				
2005	51.680.908	4.159.470	15.083.810	40.756.568
2006	56.225.305	7.451.200	45.901.250	17.775.255
2007	70.795.143	5.200.890	20.599.490	55.396.543
2008	73.729.914	5.348.620	46.893.900	32.184.634
2009	51.337.972	16.545.930	76.649.570	-8.765.668
2010	38.318.185	11.506.020	79.750.690	-29.926.485
2011	37.060.038	7.100.310	44.230.360	-70.012
2012	47.847.658	9.182.130	40.951.860	16.077.928
2013	32.207.115	9.341.310	32.686.750	8.861.675
2014	36.195.022	19.071.230	60.814.800	-5.548.548

28132670 - Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour <= 120 m³				
2005	126.000.000	12.501.250	58.840.730	79.660.520
2006	162.314.002	14.333.580	79.972.800	96.674.782
2007	235.262.645	10.018.150	90.520.250	154.760.545
2008	208.436.315	5.825.140	92.620.680	121.640.775
2009	139.624.591	4.420.660	74.812.980	69.232.271
2010	176.676.403	4.906.470	101.697.060	79.885.813
2011	196.948.988	4.569.040	98.527.370	102.990.658
2012	183.447.569	10.008.810	115.904.790	77.551.589
2013	154.822.387	11.506.710	113.133.650	53.195.447
2014	169.989.851	9.044.640	106.783.970	72.250.521

28132690 - Reciprocating displacement compressors having a gauge pressure capacity > 15 bar, giving a flow per hour > 120 m³				
2005	243.527.709	8.557.670	71.138.960	180.946.419
2006	280.713.945	15.034.680	90.412.260	205.336.365
2007	360.048.279	10.816.150	135.780.500	235.083.929
2008	387.938.554	39.719.100	138.398.000	289.259.654
2009	430.293.867	24.636.670	212.524.180	242.406.357
2010	426.281.418	68.466.220	180.620.820	314.126.818
2011	440.973.388	25.122.180	168.866.710	297.228.858
2012	381.302.525	23.086.260	278.813.610	125.575.175
2013	441.736.051	19.715.260	221.063.250	240.388.061
2014	485.282.467	36.558.150	220.725.660	301.114.957

28132730 - Rotary displacement compressors, single-shaft				
2005	162.718.786	49.159.660	57.967.630	153.910.816
2006	183.609.814	58.187.670	87.234.860	154.562.624
2007	214.102.006	38.942.570	107.167.590	145.876.986
2008	142.105.436	34.863.190	120.715.850	56.252.776
2009	78.669.368	34.365.860	126.513.350	-13.478.122
2010	95.468.865	52.934.220	129.422.320	18.980.765
2011	116.487.460	50.355.780	172.547.940	-5.704.700
2012	114.392.709	47.633.790	97.582.310	64.444.189
2013	102.124.652	37.604.370	150.952.180	-11.223.158
2014	131.138.620	52.386.390	173.457.020	10.067.990

28132753 - Multi-shaft screw compressors				
2005	1.000.000.000	12.950.870	365.802.380	647.148.490
2006	1.500.000.000	18.585.180	287.814.180	1.230.771.000
2007	1.400.000.000	11.799.250	345.968.830	1.065.830.420
2008	1.800.000.000	23.236.540	366.072.630	1.457.163.910
2009	900.000.000	11.403.810	334.193.670	577.210.140
2010	1.500.000.000	15.987.160	625.331.250	890.655.910
2011	1.800.000.000	10.229.540	783.993.040	1.026.236.500
2012	1.500.000.000	15.132.990	915.974.900	599.158.090
2013	1.200.000.000	18.279.780	850.010.540	368.269.240
2014	1.800.000.000	16.725.020	802.368.070	1.014.356.950

28132755 - Multi-shaft compressors (excluding screw compressors)				
2005	150.052.701	42.481.500	44.685.830	147.848.371
2006	129.456.610	31.650.070	69.273.280	91.833.400
2007	155.819.651	36.878.460	67.344.610	125.353.501
2008	159.275.491	48.460.100	73.498.650	134.236.941
2009	146.955.565	21.874.250	80.253.290	88.576.525
2010	179.286.856	22.810.150	109.672.240	92.424.766
2011	200.000.000	11.221.760	104.683.520	106.538.240
2012	166.849.644	4.981.950	129.159.670	42.671.924
2013	180.000.000	10.207.150	138.659.060	51.548.090
2014	206.531.600	5.489.120	141.488.770	70.531.950

28132800 - Air/gas compressors excluding air/vacuum pumps used in refrigeration, air compressors mounted on wheeled chassis, turbo compressors, reciprocating and rotary displacement compressors				
2005	619.160.642	277.221.710	397.043.960	499.338.392
2006	658.532.321	281.663.290	653.608.430	286.587.181
2007	768.636.232	292.234.000	575.654.940	485.215.292
2008	880.250.798	239.017.890	581.545.390	537.723.298

2009	767.887.760	229.758.450	687.197.910	310.448.300
2010	703.031.017	252.930.890	588.606.850	367.355.057
2011	816.213.119	220.958.190	620.358.260	416.813.049
2012	842.246.353	221.785.690	731.463.090	332.568.953
2013	898.552.276	240.083.380	500.309.560	638.326.096
2014	834.370.472	331.644.980	527.158.410	638.857.042

Table 125 Export – Import – production – Consumption by country (2014)

28132630	**28132550 Turbo-compressors, multistage**				**28132530 Turbo-compressors, single stage**				
EXPQNT	Apparent consumpti	PRODQNT	IMPQNT	EXPQNT	Apparent consumpti	PRODQNT	IMPQNT	EXPQNT	
652110	21485	0	30118	8633	1183893	0	2,418,447	1,234,554	**France**
209037	653	0	5925	5272	-24590	0	125,123	149,713	**Netherlands**
5432375	-95812	0	274044	369856	1175373	0	3,871,061	2,695,688	**Germany**
514065	25596	266	29655	4325	-281309	0	623,332	904,641	**Italy**
36952	2013888	0	2025679	11791	-327658	0	744,743	1,072,401	**United Kingdom**
1060	148389	0	148485	96	19402	0	19,482	80	**Ireland**
36313	1138	0	1165	27	8019	0	16,843	8,824	**Denmark**
772	288	0	290	2	3752	0	4,330	578	**Greece**
495	187	0	1257	1070	24809	0	31,826	7,017	**Portugal**
26608	791455	0	797531	6076	1255203	0	1,275,524	20,321	**Spain**
269507	5950	0	10049	4099	-3789	0	198,566	202,355	**Belgium**
404	68	0	68	0	1487	0	1,512	25	**Luxemburg**
0	0	0	0	0	0	0			**Norway**
45624	161882	0	162314	432	496738	0	521,532	24,794	**Sweden**
2674	757	0	780	23	285859	220	288,121	2,482	**Finland**
619830	3130	0	4447	1317	235452	0	1,383,607	1,148,155	**Austria**
0	69	0	69	0	4	0	48	44	**Malta**
1275	711	0	1030	319	-8883	0	6,243	15,126	**Estonia**
7427	-35813	0	162	35975	1360	0	1,708	348	**Latvia**
52957	-2438	0	532	2970	-3110	0	8,484	11,594	**Lithuania**
405825	-8754	0	4849	13603	876774	0	896,170	19,396	**Poland**
61368	411036	0	417719	6683	7659	0	374,571	366,912	**Czech Republic**
11055	186876	0	187207	331	-422722	0	55,003	477,725	**Slovakia**
5008	326849	0	327807	958	827595	0	2,205,241	1,377,646	**Hungary**
601	153410	0	154689	1279	-3930459	0	13,648	3,944,107	**Romania**
154	43	0	49	6	4521	0	4,707	186	**Bulgaria**
168372	668	0	1717	1049	2837	0	4,064	1,227	**Slovenia**
428	252	0	279	27	5258	0	5,973	715	**Croatia**
1295462	858247	100000	936349	178102	10447645	10632361	1,656,120	1,840,836	**EU28TOTALS**
8,562,296	4,111,963	266	4,587,916	476,219	1,413,475	220	15,099,900	13,686,654	

2813275	**28132730 Rotary displacement compressors,**				**28132650 Reciprocating displacement**							
EXPQNT	Apparent	PRODQNT	IMPQNT	EXPQNT	Apparent	PRODQNT	IMPQNT	EXPQNT	Apparent	PRODQNT	IMPQNT	
2005	19267	0	30401	11134	34367	0	35530	1163	23399	53504	622005	**France**
4287	51845	0	99910	48065	69475	0	69804	329	171684	0	380721	**Netherlands**
74483	257472	0	321336	63864	2665	0	13089	10424	3032139	20230	8444284	**Germany**
44635	-43005	0	12188	55193	15526	0	19022	3496	705198	539345	679918	**Italy**
93858	106022	0	148013	41991	94192	0	96147	1955	268219	0	305171	**United**
0	422	0	423	1	3124	0	3125	1	18283	0	19343	**Ireland**
359	791	0	1282	491	117	0	117	0	107602	5380	138535	**Denmark**
13	71	0	80	9	-49	0	30	79	44547	0	45319	**Greece**
29	-986699	0	2741	989440	247	0	285	38	57485	0	57980	**Portugal**
3762	250529	0	252529	2000	293	0	1181	888	268248	0	294856	**Spain**
18666	1666	0	4815	3149	-105	0	5024	5129	60178	0	329685	**Belgium**
5	-7	0	28	35	195	0	208	13	2043	0	2447	**Luxemburg**
0	0	0	0	0	0	0	0	0	0	0	0	**Norway**
443	148	0	2855	2707	3080	0	5756	2676	137910	0	183534	**Sweden**
1330	-2535	0	1522	4057	24	0	75	51	80610	0	83284	**Finland**
5373	2901	0	3374	473	12	0	1509	1497	-195098	0	424732	**Austria**
1	382	0	382	0	0	0	0	0	3715	0	3715	**Malta**
78	995	0	1030	35	99	0	120	21	10286	0	11561	**Estonia**
39	2352	0	2363	11	485	0	517	32	5020	0	12447	**Latvia**
278	7390	0	13968	6578	126	0	168	42	-35072	0	17885	**Lithuania**
316035	-17527	0	1014507	1032034	3800	0	3849	49	6633	0	412458	**Poland**
3284	286822	0	288829	2007	514	0	608	94	1482280	0	1543648	**Czech**
28	103	0	198	95	96	0	128	32	74540	0	85595	**Slovakia**
400	1012	0	1161	149	526	0	555	29	74018	0	79026	**Hungary**
47	2768	0	2788	20	55	0	56	1	59270	0	59871	**Romania**
5	158	0	160	2	1214	0	1397	183	17705	0	17859	**Bulgaria**
113	3244	0	4171	927	109	0	129	20	22161	0	190533	**Slovenia**
15	147	0	180	33	163	0	170	7	14587	0	15015	**Croatia**
190938	1460569	140000	1782447	461878	127941	9870	133259	15188	9421556	1104598	9612420	**EU28TOTALS**
569,571	-53,266	0	2,211,234	2,264,500	230,350	0	258,599	28,249	6,517,590	618,459	14,461,42	

28132755 Multi-shaft compressors (excluding							
Apparent	PRODQNT	IMPQNT	EXPQNT	Apparent	PRODQNT	IMPQNT	
-3238	0	3527	6765	7381	2173	7213	**France**
64321	0	66441	2120	316213	0	320500	**Netherlands**
-10692	0	3847	14539	26458	92330	8611	**Germany**
-27941	0	2239	30180	76074	103653	17056	**Italy**
-8053	672	4990	13715	-77821	0	16037	**United**
1123	0	1123	0	175	0	175	**Ireland**
126	0	167	41	784	149	994	**Denmark**
1039	0	1053	14	3672	0	3685	**Greece**
151	0	524	373	7082	0	7111	**Portugal**
5383	0	5824	441	517	0	4279	**Spain**
3788	0	6513	2725	-17240	0	1426	**Belgium**
21	0	21	0	64	0	69	**Luxemburg**
0	0	0	0	0	0	0	**Norway**
-2471	0	955	3426	788	0	1231	**Sweden**
221	0	312	91	1349	1473	1206	**Finland**
1267	0	2681	1414	-2434	0	2939	**Austria**
1	0	1	0	11	0	12	**Malta**
1088	0	2011	923	221	0	299	**Estonia**
1313	0	1382	69	263	0	302	**Latvia**
98	0	627	529	255	0	533	**Lithuania**
2193	0	4164	1971	-309085	0	6950	**Poland**
-841	0	650	1491	320	0	3604	**Czech**
1467	0	1470	3	1041	0	1069	**Slovakia**
459	0	465	6	507	0	907	**Hungary**
1738	0	1835	97	2086	0	2133	**Romania**
7047	0	7074	27	467	0	472	**Bulgaria**
-2402	0	146	2548	428	0	541	**Slovenia**
250	0	514	264	247	0	262	**Croatia**
-21114	30000	14519	65633	96498	260000	27436	**EU28TOTALS**
37,456	672	120,556	83,772	39,823	199,778	409,616	

ANNEX C: USA – DOE study on compressors

Air compressors docket: http://www.regulations.gov/#!documentDetail;D=EERE-2013-BT-STD-0040-0023

Gas compressor docket: http://www.regulations.gov/#!docketDetail;D=EERE-2014-BT-STD-0051

Extracted from DOE website 'air compressor docket' on 5 January 2016

I. Authority and Background

Title III of the Energy Policy and Conservation Act, 42 U.S.C. 6291, *et seq.*, (EPCA) sets forth a variety of provisions designed to improve the energy efficiency of products and commercial equipment. (All references to EPCA refer to the statute as amended through the American Energy Manufacturing Technical Corrections Act (AEMTCA 2012), Pub. L. 112-210 (December 18, 2012)). Part C of Title III (42 U.S.C. 6311-6317), which was subsequently re-designated as Part A-1 for editorial reasons, establishes an energy conservation program for certain industrial equipment, which includes compressors, the subject of today's notice. (42 U.S.C. 6311(2)(B)(i)) Unlike some other types of equipment included in EPCA, the term "compressors" is undefined.

Section 341 of EPCA, 42 U.S.C. 6312, provides a general statement of purpose to improve the efficiency of a variety of industrial equipment to conserve the energy resources of the Nation. Accordingly, section 341 further provides that the Secretary of Energy may, by rule, classify certain equipment as covered equipment if a determination is made that doing so is necessary to carry out the purposes of Part A-1 of EPCA. Consistent with this process, DOE is currently considering whether to regulate the efficiency of a specific group of compressors—commercial and industrial air compressors. 77 FR 76972 (December 31, 2012). DOE received comments from interested parties, which are available in docket number EERE-2013-BT-STD-0040. The comments were considered in developing a Framework Document to explain the relevant issues, analyses, and processes it anticipates using when considering new energy conservation standards for commercial and industrial air compressors. DOE issued that document and conducted a public meeting to discuss its contents earlier this year. 79 FR 6839 (Feb. 5, 2014).

Because the term "compressors" is undefined by EPCA, DOE considered a variety of definitions for this term in order to help ensure a reasonable level of clarity with respect to the type of equipment that might be regulated. In its ongoing proceeding, DOE offered for comment the following definition for "commercial and industrial compressors" to clarify the coverage of any potential test procedure or energy conservation standard:

Compressor: A compressor is an electric-powered device that takes in air or gas at atmospheric pressure and delivers the air or gas at a higher pressure. Compressors typically have a specific ratio, the ratio of delivery pressure to supply pressure, greater than 1.20.

After further evaluating this definition and considering the comments it received, DOE revisited this definition and offered a revised version. That version, which is based on International Organization for Standardization (ISO) Technical Report (TR) 12942, provides a different definition of the term "compressor" from DOE's initial approach. (ISO TR 12942 provides a means to classify modern compressor types along with definitions and related terms that can be utilized in technical and contractual specifications such as a manufacturer's literature and industrial statistics.) The revised definition DOE offered for public comment reads as follows:

Compressor: A machine or apparatus converting different types of energy into the potential energy of gas pressure for displacement and compression of gaseous media to any higher pressure values above atmospheric pressure with pressure-increase ratios exceeding 1.1. [(1)]

DOE is continuing to consider revisions to this definition, however, due at least in part to submitted comments in which some parties have commented that the specified ratio should be different to avoid overlapping with what the compressor industry generally treats as "blowers," equipment for which DOE may also establish standards. See 78 FR 7306 (Feb. 1, 2013) (announcing DOE's issuance of a framework document related to the potential setting of energy conservation standards for industrial fans and blowers).

DOE notes that the vast majority of compressors are air compressors. According to Current Industrial Reports from the U.S. Census Bureau, [(2)] shipments of new air compressors totalled 3.8 million in 2006, while shipments of new gas compressors were only around 6,000 units. As such, DOE at this point is considering establishing standards that would address only those compressors intended to compress air. [(3)]

While DOE's focus up until now has centred primarily on those compressors that are intended to compress air, compressors are used in a wide variety of applications and may be used to compress different types of gases. DOE is aware that compressors intended to compress other gases such as natural gas (i.e. gas compressors) may, both collectively and individually, use a substantial amount of energy, as such compressors are often very large. An important application of gas compressors is the pipeline transport of natural gas. The drivers for such compressors can be natural gas turbines (particularly since gas is an easily accessible fuel out in the field), steam turbines, internal combustion engines, or electric motors. Recent data provided by the Energy Information Administration (EIA) indicate that the annual amount of natural gas used to transport natural gas through the pipeline system was about 0.7 quadrillion Btu. In addition to the pipeline natural gas use, compressors are used in the production and processing of natural gas, which is accounted for in the 1.4 quadrillion Btu of natural gas reported by EIA as "lease and plant fuel." [(4)]

In the Framework Document, DOE stated that it is considering the possibility of setting air compressor standards based on equipment size as measured in rated horsepower (hp). This approach would help align its efforts with the current energy efficiency standards for electric motors, as codified in subpart B of Title 10 of the Code of Federal Regulations, Part 431 (10 CFR part 431) by covering compressor equipment rated from 1 through 500 hp. Because compressors often rely on the use of an electric motor to operate, aligning compressor standards in this manner could provide a relatively straight-forward approach that parallels the approach already established for electric motors. DOE may take a similar approach with respect to gas compressors as well but seeks comment on the appropriateness of doing so.

To inform its decision making regarding gas compressors, DOE requests information, comment, and supporting data about the characteristics, applications and energy use of gas compressors. In particular, DOE seeks comment and information about the topics below.

II. Discussion

DOE seeks a variety of different types of information to help inform its decision regarding how, if at all, to regulate gas compressor energy efficiency. To this end, DOE seeks detailed data regarding the following aspects related to gas compressors:

1) Annual shipments.
   a) DOE is seeking historical shipments data (specifically from 2003-2013) for gas compressors, with further breakdowns, where available, including, but not limited to, equipment type (both compression principle and driver type), equipment size, and application. DOE is also interested in comments regarding how gas compressors are manufactured and shipped as original equipment from the manufacturer, for example, as a package (i.e., with both air end and primary driver), or as a separate component, or both.
2) Equipment types and sizes.
   a) DOE is seeking comment regarding the types of equipment used in gas compressors. Specifically, DOE is interested in information regarding the compression principles (e.g., positive-displacement or dynamic compressors) and primary driver types (e.g., natural gas or steam turbines or electric motors) used in gas compressors, as well as what design, construction, and performance characteristics would be attributed to each type. DOE is also interested in information regarding the compression principles and driver types used in gas compressors based on application type.
   b) DOE is also seeking comment regarding how gas compressors are sized (e.g., by brake horsepower, input/output pressure, or delivered air volume) and the general sizes of gas compressors based on both equipment and application type.
3) Applications.
   a) DOE is aware that an important application of gas compressors is in the transportation, production, and processing of natural gas. DOE seeks comment on other major

applications (e.g., injection, withdrawal, lifting, or filling) in which gas compressors are used.
b) DOE also seeks information regarding any particular characteristics or features that are unique to each of these different applications.

4) Typical energy use in each application type.
DOE seeks comment regarding the typical energy use of gas compressors broken down by, where available, application type, equipment type, and equipment size.
5) Typical energy efficiency by equipment type.
DOE is interested in information regarding the typical range in efficiency levels of gas compressors broken down by equipment type and size.
6) DOE is interested in what opportunities, if any, for improving gas compressor energy efficiency are possible and how these efficiency improvements may, or may not, impact equipment performance, features, utility or safety.
7) DOE requests comment on whether the test procedures in ISO1217:2009 (5) and ISO 5389:2005, (6) which address the testing of displacement and turbo compressors, respectively, would be appropriate for rating gas compressors. DOE also requests information on other applicable test procedures it should consider along with any deficiencies or issues that would need to be addressed prior to adopting a regulation mandating a particular test procedure.
8) DOE requests feedback regarding any safety issues, regulations, codes, or standards (e.g., National Fire Protection Association requirements) that must be considered in the manufacture, testing, and use of gas compressors.
9) DOE seeks information on any voluntary efforts by manufacturers that are already in place to improve the energy efficiency of gas compressors and what type of future voluntary efforts to improve efficiency, if any, are likely to occur in the near future.
10) DOE seeks information regarding whether there are particular characteristics that would readily distinguish an “air compressor” from a “gas compressor” and whether those characteristics play any role with respect to the energy efficiency performance of these two categories of compressors.
11) DOE requests comment on the market for natural gas compressors, and how they are marketed, sold, shipped, and assembled.

[etc.]

ANNEX D: Oil-free air applications

In general the following main application areas can be identified[210,211]:

1) Oil and Gas
   a) upstream (off shore / on shore)
   b) midstream
      i) Cleaning and dewatering equipment
      ii) Drying and dehydration equipment
      iii) Inspection
      iv) Leak testing
      v) Pressure testing
      vi) Sandblasting
      vii) Purging & Packing
      viii) Displacement
      ix) Insulation
      x) Waste water treatment
      xi) Electricity supply
   c) downstream
      i) Catalytic cracking
      ii) Catalyst regeneration (24bar)
      iii) Drying
      iv) Flaring
      v) Sandblasting
      vi) Breathing air
      vii) Desulphurisation
      viii) Plant air
      ix) Pipeline services
      x) Air separation - compressed air for air, nitrogen and oxygen component separation
      xi) Purging
      xii) Pressure testing
      xiii) Pneumatic conveying - compressed air for pneumatic transport of materials such as PVC, PTA and DMT chips
      xiv) Instrument air, to operate valves etc.;
      xv) Waste water treatment
      xvi) Electricity supply

---

[210]Source: http://www.atlascopco.com/

[211]Listlargelybasedon:http://www.ingersollrandproducts.com/am-en/solutions/oil-free/industries-served.LastaccessedDecember2015

2) Power plants
   i) Nuclear dome testing
   ii) Induction loop testing - portable generators of more than 500kVA
   iii) Instrument air;
   iv) Leak testing;
   v) Over speed testing;
   vi) Cleaning air;
   vii) Flue gas desulphurisation;
   viii) Sandblasting
   ix) Breathing air
   x) Pipeline services
   xi) Waste water treatment
   xii) Electricity supply
3) Manufacturing industry
   a) Air Separation
      i) Nitrogen supply
      ii) Breathing air
      iii) Electricity supply
   b) Automotive
      i) Instrument air;
      ii) Pneumatic tools, robot operation;
      iii) Cleaning air (surface preparation);
      iv) Cooling air;
      v) Process air for pneumatic tools & robots
      vi) Spray painting using air, agitation of paint baths;
      vii) Waste water treatment;
      viii) Electricity supply;
   c) Electronics
      i) Instrument air - for picking, pressing, drilling, moving and placing electronic components
      ii) Process air
      iii) Cleaning air - for cleaning and polishing PCB's, removing chemical deposits on wafers after etching, cleaning air knives in LCD panel manufacture
      iv) Nitrogen soldering - compressed air for nitrogen generators
      v) Waste water treatment
      vi) Electricity supply
   d) Food & Beverage
      i) Instrument air 100% oil free air
      ii) Cleaning air
      iii) Pneumatic conveying

- iv) Aeration
- v) Fermentation
- vi) Modified atmospheric packaging (MAP) - compressed nitrogen
- vii) Cooling & Spraying
- viii) Breathing air
- ix) Packaging equipment
- x) Waste water treatment
- xi) Electricity supply

e) Glass
- i) Cooling air
- ii) Glass blowing
- iii) Float glass manufacturing
- iv) Waste water treatment
- v) Electricity supply

f) Metal
- i) Combustion air
- ii) Instrument air
- iii) Process air
- iv) Sandblasting
- v) Flue gas desulphurisation
- vi) Cooling air
- vii) Coating air
- viii) Breathing air
- ix) Waste water treatment
- x) Electricity supply

g) PET Industry
- i) PET blowing
- ii) Instrument air
- iii) Cleaning air
- iv) Pneumatic conveying
- v) Waste water treatment
- vi) Electricity supply

h) Pharmaceutical
- i) Instrument air
- ii) Modified atmospheric packaging (MAP) - compressed nitrogen
- iii) Fermentation - for bacteria during fermentation
- iv) Cooling & spraying
- v) Pneumatic conveying - pneumatic cylinders, control valves and components
- vi) Aeration - for oxidation processes
- vii) Cleaning air

- viii) Packaging equipment air
- ix) Waste water treatment
- x) Electricity supply

i) Pulp & Paper
- i) Instrument air
- ii) Cleaning air
- iii) Cooling air
- iv) Process air - for clean production and efficient maintenance
- v) Waste water treatment
- vi) Electricity supply

j) Ski Industry
- i) Feed air for snow guns - up to 10.3 bar for snow cannons
- ii) Pressure testing - up to 10.3bar
- iii) Electricity supply

k) Textile
- i) Spinning - to push through the fine nozzles
- ii) Weaving - to blow through fine nozzles to transport the weft
- iii) Dyeing
- iv) Texturizing - jets of clean air to push through the nozzles
- v) Winding & coning
- vi) Waste water treatment
- vii) Electricity supply

l) Waste Water Treatment
- i) Instrument air
- ii) Aeration
- iii) Inertisation of sludge digesters
- iv) Leak testing
- v) Sandblasting
- vi) Cryogenic cleaning
- vii) Electricity supply

4) Mining
- i) Instrument air
- ii) Pneumatic tools
- iii) Cleaning air - for a wide range of cleaning applications
- iv) Ventilation and breathing air
- v) Drilling air - high power wheeled units for deeper drilling
- vi) Lighting
- vii) Waste water treatment
- viii) Electricity supply

Please note that this is NOT an exhaustive overview and more processes requiring oil free air may exist.

ANNEX E: Low pressure applications (WWT + conveying)

The following sections describe the main low pressure applications waste water treatment and pneumatic conveying in more detail.

Waste water treatment

Aeration of basins in waste water treatment (WWT) is presumably the single largest application of low pressure compressors. Wastewater can be domestic wastewater, wastewater from institutions, industrial wastewater, infiltration into sewers, storm water, leachate and septic tank wastewater[212]. Aeration is applied in the activated sludge process.

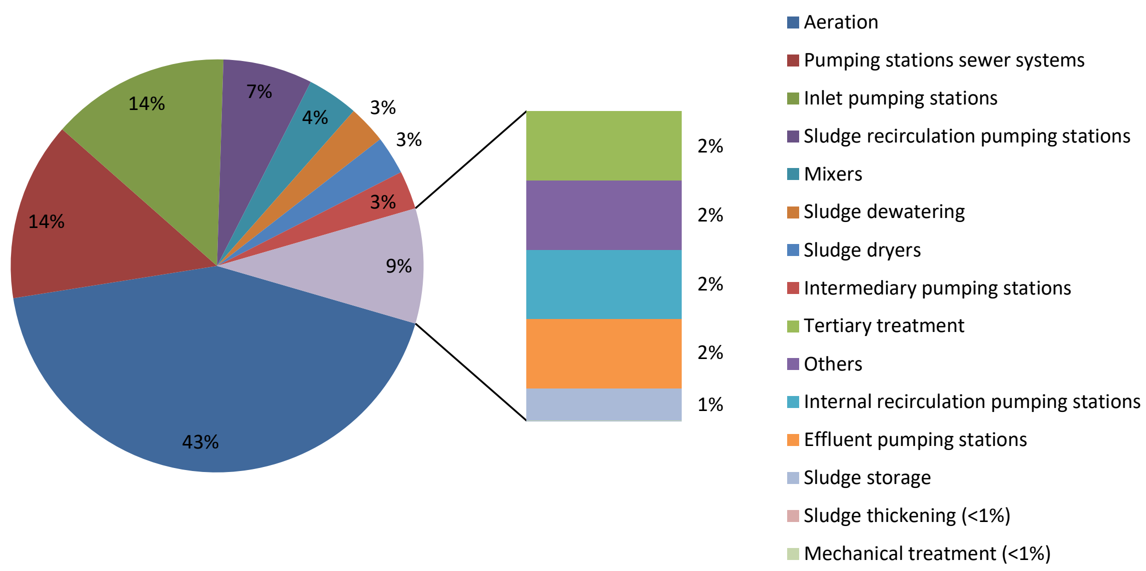
Activated sludge

The activated sludge process relies on the injection of air ('aeration') into tanks containing wastewater to encourage the large scale growth of natural bacteria that break down the impurities the water contains. Oxygen is bubbled through the wastewater to reduce biochemical oxygen demand (BOD) and chemical oxygen demand (COD), producing an effluent with a low turbidity and nitrogen levels. The tanks or basins allow a continuous flow of influent.

Most of WWT energy is for aeration: The energy requirement for aeration is often more than 40%, sometimes 50-70% of the overall plant energy consumption (the figure below by Aquafin shows 43%).

An aeration tank requires constant pressure (the water level, or pressure applied to the discharge point of the compressor is constant). Typical values are around 6 m of water pressure. This converts to some 0.6 bar pressure differential (ignoring water temperature (affects density) and actual atmospheric pressure). Aeration tanks operate continuously.

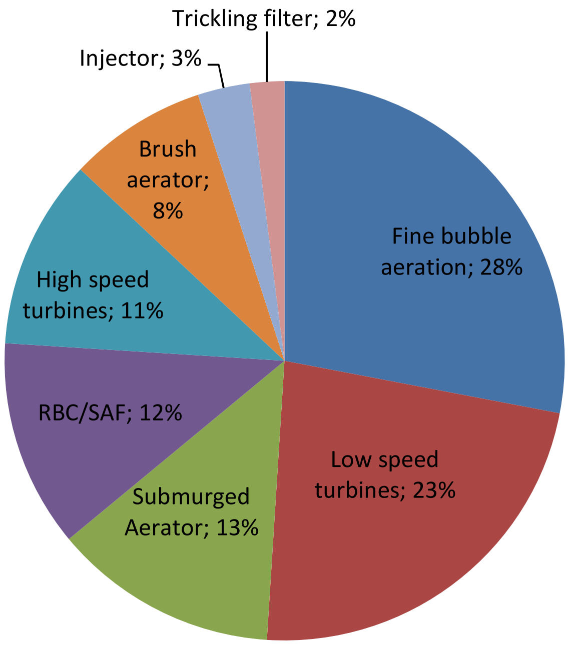
Figure 94 Energy in waste water treatment (Source: presentation by Aquafin, June 2015)



[212] http://ocw.unesco-ihe.org/pluginfile.php/463/mod_resource/content/1/Urban_Drainage_and_Sewerage/5_Wet_Weather_and_Dry_Weather_Flow_Characterisation/DWF_characterization/Notes/Presentation%20handouts.pdf

Different types of aeration have been applied, partly depending on year of installation (state-of-art at time), partly depending on capacity required. Most common are fine bubble aeration, low speed turbines, submerged aerators, RBC/SAF, high speed turbines, brush aerators.

Figure 95 Types of aeration applied by Aquafin 2015[213]



The submerged aerator, the low-speed and high-speed turbines are basically impellers that are sunk into (submerged = sitting on bottom of basin, low speed = hung overhead or floating, high-speed = floating) in the water basin[214]. RBC is a rotating biological contactor, SAF is a submerged aerated filter which may also use regenerative blowers.

Each aeration technique can be characterised by an SAE - Aeration efficiency in standard conditions in clean water, expressed in kg_{O2}/kWh.

Table 126 Aeration efficiency in standard conditions[215]

Aerator Type	SAE kg_{O2}/kWh
High-speed surface aerator	0.9 – 1.3
Low-speed surface aerator	1.5 – 2.1
Coarse-Bubble	0.6 – 1.5
Turbines or jets (coarse bubbles sheared into fine bubbles)	1.2 – 1.8
Fine-Pore (fine bubbles)	3.6 – 4.8

Fine-bubble aeration is one of the more efficient aeration systems of today.

[213] Source: presentation by Aquafin, June 2015.

[214] http://www.europelec.com/the-low-speed-turbine-tlf.html and http://www.sulzer.com/en/Products-and-Services/Compressors-and-Aerators/Submersible-Aerator-Type-ABS-XTA-XTAK

[215] Aeration, M. K. Stenstrom and D. Rosso, University of California – Los Angeles, University of California – Irvine, Feb 8, 2010

Considering all the above VHK estimates that approximately 1/3 of the Aquafin installations is using low pressure air for aeration (fine bubble + some SAF). The others involve mainly mechanical agitation. Of the fine bubble "low pressure" WWT systems, the share of low pressure in the overall energy consumption is likely to be less than the 43% as calculated for Aquafin, as this share includes these other less efficient processes as well[216]. Even if a conservative approach is taken, keeping the share of aeration energy for low pressure aeration at 43%, the share of low pressure aeration in the total energy consumption of WWT is 43% (share aeration in total WWT energy) * 33% (share low pressure in aeration technologies) is 14% of the total Aquafin energy consumption.

Lack of similar data at EU level prohibits making a similar assessment for the EU as a whole. However, even if the share of low pressure is doubled it still remains below 50% of the total EU energy consumption for WWT.

Sequencing batch reactor (SBR)

Sequencing batch reactors (SBRs) are a variation of the activated-sludge process, as they combine all of the treatment steps and processes into a single basin, or tank, whereas conventional facilities rely on multiple basins and continuous flow. The SBR accomplishes equalization, aeration, and clarification in a timed sequence in a single reactor basin.

SBRs consist of one or more tanks (equipped with a common inlet so that one tank can be in settle/decant mode while the other is aerating and filling). The tank(s) has/have a “flow through” system, with raw wastewater (influent) coming in at one end and treated water (effluent) flowing out the other.

Aeration times vary according to the plant size and the composition/quantity of the incoming liquor, but are typically 60 to 90 minutes[217].

Extended aeration plants are more flexible in flow rate, eliminating restrictions presented by pumps located throughout the SBR systems.

Digesters

Digesters are used to stabilize the solids that are removed from the wastewater during treatment. The goal is to reduce the mass of the sludge and convert it into a non-hazardous form so that it may be handled or used with minimal health hazards. Air may injected in to the sludge, so that it floats to the top and can be removed by a skimmer. This process is usually used on secondary sludge from activated sludge tanks[218].

SBR and digesters may require varying pressure levels, and frequent start-stops.

User profile and technology profile

In virtually all communal WWT the required capacity (volume flow rate) is variable. The discharge pressure is rather constant (depends on water column of activated sludge basin).

The technologies used for waste water aeration are:

1) Positive displacement:
    a) lobe
        i) twin-lobe
        ii) tri-lobe
    b) screw

---

[216] But it could also be argued that fine bubble is responsible for a larger share of total energy consumption, as these may be relatively large plants, and the other technologies are mainly smaller plants. Therefore the calculations of final share of low pressure is still based on 43%.

[217]https://en.wikipedia.org/wiki/Sequencing_batch_reactor

[218]http://www2.humboldt.edu/arcatamarsh/digester.html

   c) vane
   d) tooth
2) Dynamic:
   a) centrifugal
      i) single stage (with either a high speed electric motor, or integrally geared drive)
      ii) multi-stage
      iii) side channel

For activated sludge aeration, using fine bubbles, the need for air is continuous but variable as the required flow rate can vary depending on rain fall, use of toilets, etc.

The dominant technology applied for WWT aeration has been the lobe 'blower'. Starting from straight two-lobe geometries, the product offering now includes 'tri-lobe', which is much quieter, and 'helical lobes', which offer less pulsations resulting in again lower noise and better package efficiency.

However, other competing technologies have entered the market, avoiding known drawbacks of lobe technology such as efficiency, pulsations in discharge air, noise, maintenance. High speed centrifugal compressors driven by variable speed drives are now considered state-of-the-art with products offering a turn down of 50% or even 30% of the volume flow at full load

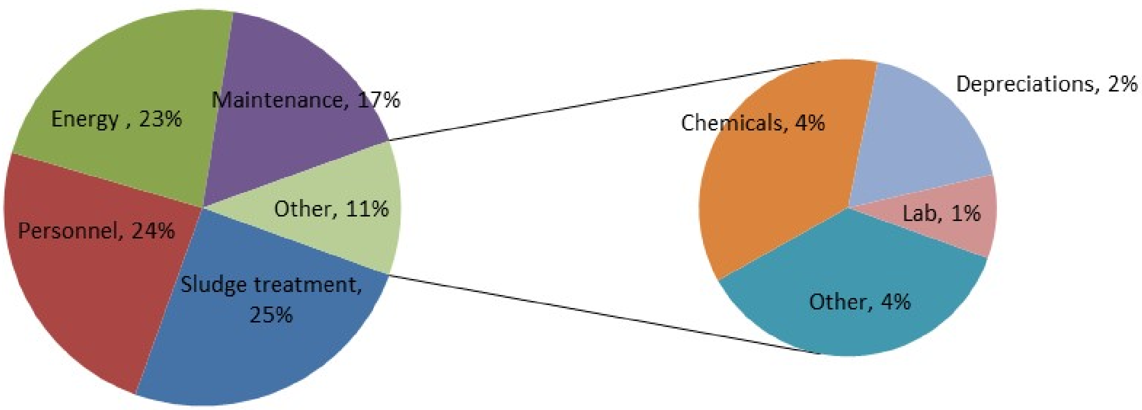
For SBR and digesters, the need for air is discontinuous, and frequent start-stop occurs. For these applications positive displacement compressors are still considered state-of-the-art, whereby screw compressors may provide certain advantages compared to lobe compressors.

The volume flow rates depend on the type and capacity of the wastewater treatment facility, and can range from only tens of m^3/h to over 50 000 m^3/h or even 500 000 m^3/h for metropolitan installations. The discharge pressure may range from a few hundred mbar (indicatively 300 mbar(g)) to 2 bar(g). The power requirement may range from less than 1 kW for the smallest (approximately 20 m3/h at 300 mbar) to over 700 kW for the largest in this range (beyond 15 000 m3/h at 1 bar(g), low pressure screw type).

Costs

The costs of energy for aeration are also substantial: some 23% in the Aquafin example.

Figure 96 Costs in waste water treatment ([219])



Sludge treatment bears also substantial costs. The sludge (thickened residue) is not always treated on site, but may require transportation to centralised sludge digesters.

[219] Source: presentation by Aquafin, June 2015

WWT Energy Consumption

It has been stated that the overall energy consumption related to aeration of waste water treatment represents some 1% of a nation's electricity consumption[220]. Scaled up to EU28 this translates to some 20-30 TWh/a[221]. This overall figure is confirmed by other sources / calculations:

1. According the European Commission the 'load' imposed on EU WWT is some 495 million people equivalents ('pe') per day[222]. Assuming 5 pe is equivalent to 1 m^3 of effluent the total effluent to be treated is 9.9 million m^3 per day. If it is assumed that the average WWT energy consumption is 0.5647 kWh/m^3 the total consumption is 20 TWh/a for the whole EU. Of this maximum 70% is due to aeration, which is 14 TWh/a.

   This corresponds to a continuous power input of 1.6 GW. Assuming the compressor is oversized by a factor three the installed (nominal) power is 4.8 GW.
2. According the EC223 the load for urban WWT is some 671 million p.e. (applies to EU27, but the error is assumed negligible). A benchmark study224 shows that there are large differences in the specific energy demand for WWTs in North West-Europe. The overall energy consumption ranges from 27.7 kWh/(p.e.*year) to 45.3 kWh/(p.e.*year), with an average value of about 32.1 kWh/(p.e.*year)225. Taking an EC load of 671 million p.e. and the average of 32.1 kWh/(p.e.*a) a total consumption of urban WWT of almost 22 TWh/year is calculated for WWT alone (the min/max are 19 to 30 TWh/y). Of this 22 TWh only a fraction is related to production of (low pressure) air. Sources state that between 50-70% of WWT energy can be due to aeration. This results in 11 to 15 TWh/a for aeration in WWT. The lower figure (with close to 50% of energy for aeration) is closer to what is stated in a publication by a major supplier of relevant equipment [226]. The higher value, 15 TWh assumes a default of 70% of energy for aeration.

The above sources however do not take into account that there are also other technologies deployed for aeration (such as turbines, agitators, etc.), and that within the total range of technologies, the fine bubble aeration is one of the most efficient. In the section "Activated sludge" of this Annex it was calculated that for a major WWT organisation in Belgium , the share of low pressure in the total WWT energy is probably closer to 14% when correcting for other technologies.

When adopting an even more conservative approach, the estimated share of low pressure in the total energy consumption of WWT in Europe could be set two (~30%) or three times (~50%) higher than the 14% share calculated before (as the Belgium example may be skewed). Assuming that the share of low pressure applications in WWT in the total energy consumption is 50% of the total, this results in 5 TWh/a. The remaining 9 TWh (14 TWh for "general aeration" minus 5 TWh for "low pressure aeration ") can be attributed to other technologies in use for aeration in WWT but which are outside the scope of this study. One can also conclude that the remaining 5 TWh for low pressure applications can be allocated to pneumatic conveying and other low pressure applications.

---

[220] http://lontra.co.uk/technology/applications/

[221] Total EU electricity demand is approximately 2800 TWh (indicative for period 2010-2015).

[222] 1 p.e. (population equivalent)" means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day

[223] Environmental, economic and social impacts of the use of sewage sludge on land, Summary Report 2 Baseline Scenario, Analysis of Risk and Opportunities, Service contract No 070307/2008/517358/ETU/G4, p.5, Table 9 Total number of agglomerations in EU27 and total generated organic pollution load discharged (CEC 2006).

[224] Innovative Energy Recovery Strategies in the urban water cycle - Final report INNERS project, Author(s): All INNERS partners, under revision by Katrien Bijl, projectmanager INNERS.

[225] 0.54 kWh/m3 for treating and transporting waste water.

[226] http://www.energy.siemens.com/hq/en/compression-expansion/special-applications/aeration/

Pneumatic conveying

Probably the second largest application area for low pressure air is pneumatic conveying. Pneumatic conveying is a core technology in the development of bulk material handling systems for the process industries. Pneumatic conveying technologies are divided in vacuum conveying and pressure conveying.

Table 127 Vacuum Conveying and Pressure Conveying Compared

Vacuum Conveying Advantages	Pressure Conveying Advantages
Most often a lower cost system	Better rate and performance
Much easier (and smaller) at pick-up	Much easier for multiple destinations
Less dusting (better containment)	Smaller receiver / separator
Less likely to cause temperature problems	Ideal for long distance conveying
Best employed when the product is to be conveyed from several feeding points to one delivery point. Product entry is simple and dust-free as there is no excess pressure	Pressure conveying is best employed where the product is to be conveyed from one feeding point to several delivery points over long distances. Airlocks or pressure vessels are required to introduce the material into the system. Product delivery at the destination is simple.
In vacuum conveying, no moving parts contact the materials, no dust escapes into the atmosphere and no contamination can enter the system.	Pressure conveying is extremely efficient because material can be moved in larger quantities and at longer distances.

Both pressure or vacuum systems have their advantages, and choosing the best conveying method depends on the final application. Often pressure conveying systems are combined with vacuum conveying systems in a single application.

The most common four types of conveying are: lean-phase (or dilute-phase), low-velocity, semi-dense phase and dense-phase conveying. Both vacuum conveying and pressure conveying systems may employ the dilute phase or dense phase principle of operation. As vacuum pumps are outside the scope of the study, the remainder of the section deals with pressure-conveying.

In lean (dilute) phase conveying, the material to be transported is suspended in the transport air, it flows as particles in an air stream.

In dense phase conveying, the material to be transported is 'kind of' pushed forwards by a 'plunger' made up of compressed air. It is more a peristaltic movement, with the material being delivered in batches (although the stream is continuous).

User profile and technology profile

For pressure conveying, it is important that the equipment can withstand fluctuations in pressure and maintains continuous air flow.

This is particularly a problem in lean phase suspension flow systems where the conveying air velocity is relatively high.

In a lean phase system the conveying air velocity is typically 20 m/s, which means that air transverses a 100 m long pipeline in only 5 s. In order to convey materials reliably in pneumatic conveying systems, a minimum value of conveying air velocity must be maintained. For lean phase conveying systems this minimum velocity is typically of the order of 15 m/s. If a surge in the feed rate causes a higher pressure drop over the line and lowers air speed by more than about 10 or 20 percent, this can result in a blocked pipeline.

For this reason centrifugal turbo compressors are not often used because the flow rate depends on the pressure. The performance curves for regenerative (side-channel) blowers are generally better suited to conveying than those of the centrifugal compressors, but they are not as good as those for positive displacement machines. Positive displacement machines, for which the volumetric flow rate is largely independent of the discharge pressure, are less likely to cause this type of system failure[227].

For dense phase conveying the main risk is a blockade of materials: Usually the pressure builds up to a point the blockade is 'flushed away', resulting in a **pressure peak**.

The use profile is thus variable pressure for both lean- or dense-phase. The volume flow rate can be variable or constant for dilute-phase conveying, but constant for dense phase conveying (in conveying the pipe length determines the pressure drop, resulting in increased air velocity at the far end of the pipe. For lean-phase this air velocity needs to be controlled, otherwise material failure may occur).

The technologies used for pressure conveying are:

Table 128 Technologies for lean and dense phase conveying

	Lean-phase	Dense-phase
Lobe	x	
Screw	x	x
Dry screw (higher pressure than screw blower)		x
Vane	x	
Tooth	x	
Single stage turbo	x	x
Multi stage turbo	x	x
Side channel	x	

It is essential that the operating characteristics of the machine are related to the extreme requirements of the system.

The volume flow rates depend on the type and capacity of the conveying installation facility, and can range for lean conveying from only tens of m^3/h to over 50 000 m^3/h. The discharge pressure may range from a few hundred mbar (indicatively 300 mbar(g)) to maximum 2.5 bar(g). The power requirement may range from less than 1 kW for the smallest (approximately 20 m^3/h at 300 mbar) to over 700 kW for the largest in this range (beyond 15 000 m^3/h at 1 bar(g), low pressure screw type).

For dense phase conveying the volume flow ranges from some 500 m^3/h to some 20 000 m^3/h at discharge pressures between 1 to beyond 4 bar(g). The smaller ones require an input power of less than 5 kW (at 400-500 mbar(g) and some 200 m^3/h flow). The largest requires a power input of over 600 kW (2.5 bar(g) at volume flow between 5 000 to 10 000 m^3/h.

[227] http://machineryequipmentonline.com/hydraulics-and-pneumatics/air-movers-types-of-air-mover-and-aerodynamic-compressors/

ANNEX F: Swiss study

Extrapolating to EU28

In July 2000 a study[228] commissioned by the Swiss Bundesamtes für Energie analysed possible energy savings in compressed air systems in Switzerland. It included a market analysis based on a survey sent to the seven largest suppliers of compressed air products.

The survey showed that sales of oil-free compressors are approximately 1/7 of sales of lubricated piston or screw compressors.

Table 129 Sales of compressors per power and category in Switzerland 1998 (based on 7 largest suppliers)

Compressor power	Oil-free compressors			Piston compressors		Screw compressors		Total	
kW	*2-4 bar*	*4-10 bar*	*> 10 bar*	*< 11 bar*	*>11 bar*	*< 5 bar*	*5-13 bar*	*count*	*kW*
1.5		20		333	10		13	376	564
2.2		28		158	7		40	233	513
3		7		244	24		3	278	834
4		20		91	148		50	309	1236
5.5		8	1	89	5		148	249	1370
7.5		13	5	55	9		234	316	2370
11		12		23	1		153	189	2079
15		9		18			125	152	2280
18.5		4					59	63	1166
22		5					74	79	1738
30		4					56	60	1800
37		3					59	62	2294
45		2		1			29	32	1440
55	1	2					25	28	1540
75	1	3	1				27	32	2400
90		3		1			4	8	720
110		3					4	7	770
132	1	1					6	8	1056
160	1	1					1	3	480
200		1					11	12	2400
250		3					4	7	1750
Total	**4**	**152**	**7**	**1013**	**204**	**0**	**1123**	**2503**	**30799**
Avg. power	106	22	17	3.46	3.92		20		**62**
Share per category	2.5%	93.3%	4.3%	83.2%	16.8%	0.0%	100.0%		

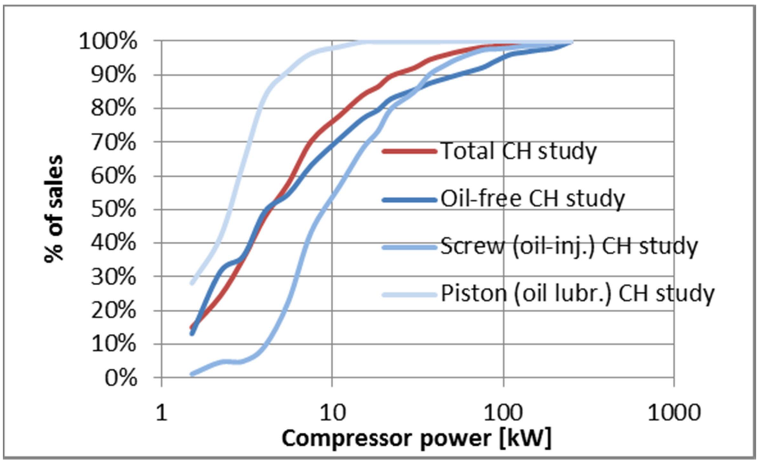
The study was limited to compressed air systems with a +1 kW rating (presumably nominal motor output power) and gauge pressure between 2 – 15 bar (is 3-16 bar absolute). The scope is therefore not fully aligned with the scope of this study: especially lower pressure products are not covered.

[228] http://www.energie.ch/themen/industrie/druckluft

The data shows that, in Switzerland, the majority of oil-free sales is in the range of 4 bar(g) or higher (98% of total) which in this study is called "oil-free". The average power of all oil-free in the range 2-14 bar(g) is 23 kW, but when expressed by discharge pressure 2-4 bar(g), 4-10 and >10 the differences are more pronounced, respectively 106, 22 and 17 kW.

Piston sales are mainly in the low power range (average < 4 kW). Screw compressors are sold over the entire range (average 20 kW).

Figure 97 Sales as % of sales per category (piston, screw and oil-free) and total



The Swiss study shows that 50% of OF sales are below 10 kW, 85% of sales are below 55 kW, and 97% of sales are below 200 kW, etc.

Sales of lubricated piston and screw compressors in Switzerland in 1998 is 2340 units in total. With GDP of Switzerland being approximately 1/30 of that of the EU, the GDP corrected EU sales would result in 70200 units (2340*30) which is only 62% of the figure estimated as market size in the former Lot 31 study (estimated 113 400 units in year 2000). Correction on the basis of the number of employees in Switzerland (some 1/50 of the EU28) gives a fairly good alignment (total 117 000). Weighting on basis of employees is preferred over GDP.

Extrapolating the Switzerland sales of oil-free compressors (range 2-15 barg) results in 933*50 is 46 650 units in year 1998. This figure is much higher than estimated in the former Lot 31 study (estimated 20 000 units in year 2000). The relative high sales figure in Switzerland of oil-free compressors may be explained by the market characteristics that may be different to that of average EU. There is not sufficient information to explain this difference in more detail.

In absolute numbers sales of oil-free compressors are dwarfed by sales of piston and screw compressors by a factor 7 (screw vs oil-free) to 7.5 (piston vs oil-free).

Sales of pistons are particularly high in the low motor rating area, some 91% of piston sales is with a motor rating of less than 7.5 kW.

Table 130 Swiss sales per category and size

	Oil-free			Piston		Screw	
	2-4 bar	4-10 bar	> 10 bar	< 11 bar	>11 bar	< 5 bar	5-13 bar
less than 3 kW		**34%**		**64%**		**5%**	
less than 7.5 kW		**52%**		**91%**		**23%**	

Share of sales	2.5%	93.3%	4.3%	83.2%	16.8%	0.0%	100.0%
avg. power (kW)	106	22	17	3	4	**(-)**	20

In the former lot 31 study sales of oil lubricated pistons in 2011 at EU level was estimated to 52 000 (49% of total 105 800) and that of (oil-injected) screw and vane some 53800 (51% of total) [229]. The CH sales are fairly consistent with piston sales of 52% of total and screw some 48% of total (not including oil-free).

Table 131 Swiss sales compared to first Lot 31

	Lot 31, Final Report 7 April 2014		CH sales 1998	
	Volume 2011	**Avg power (kW)**	**Volume CH 1998**	**Avg power (kW)**
fixed speed OIS+OIV	45 200	24,7	1125	20
variable speed OIS+OIV	8 600	35,4		
pistons	52 000	4,3	1217	3.5
Totals	105 800			

If indeed the CH sales can be considered sufficiently representative for the whole EU, the total oil free sales should be some 1/7th of the piston/screw sales.

For the EU 28 based on former Lot 31 study, this results in some 50000/7 = 7000 units, in the range from low pressure (<4 bar in CH source), to standard pressure (> 4 bar). Some 1/3rd of these 7000 units would be in the motor range of 3 kW or lower and can be assumed to be single phase (these could be oil-free reciprocating compressors, used in small shops, possibly even dental applications). Some 52% is less than 7.5 kW. This leaves some 4700 units (2/3rd) to 3500 (1/2) in the range of 4 kW and higher, of which most can be assumed to be three-phase driven (especially if above say 7.5 to 11 kW). Some 37% of oil-free is 11 kW or higher.

The source for the CH data does not state whether the 'oil-free' compressors include turbomachinery, or whether compressors for applications requiring 1.1 to 2 bar(a) are excluded from the overview.

[end]

[229] Lot 31, Final Report task 1-5, Task 2, Table 3 3 Sales 2nd survey (compared to 1st survey), p.106