Energy efficiency in industrial compressed air generation

Survey about developments, trends and alternative generation technologies

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1. Introduction

1.1. Background

Compressed air is widely used in industry as a cross-cutting technology in many areas of application as working, active or process air, for generating vacuum or for control and test applications. Compressed air is discussed as one of the most energy-intensive energy sources in industry; here generally electrically driven air compressors are used for the production of compressed air. In the European Union in 2001 these compressors accounted for about 10 % of the total electric power used in industry. In Germany in 2008 the figure is about 7.3 % (about 17 TWh) (Fraunhofer ISI 2010).

Considering the energy conversion chain beginning with a primary energy source up to compressed air, it shows that firstly a primary energy source is converted to electrical energy in a power plant. This electrical energy then is provided to an electric drive and again converted into mechanical power to eventually drive a compressor which compresses ambient air to the required pressure level. Each of the conversion or transfer stages is afflicted with losses.

In view of this process, the question arises whether compressed air could be provided using an alternative approach for industrial applications. As to this question literature is only available in limited scale, a series of interviews with experts in the field of compressed air generation and possible alternative drive concepts was carried out following an exploratory analysis of available literature.

The aim of the interviews was to obtain an overview of the expert's assessments on alternative approaches for generating compressed air and discuss these alternatives for their potential applicability in industry. Focus was not on the study of specific applications, but the basic discussion of possible alternative technologies. The present document provides an overview of the results of these discussions; the basis of this article constitutes Roessler (Roessler 2011).

1.2. Framework and study design

For the purposes of narrowing the viewing object only the delivery of compressed air was analyzed. The „compressor“ as a combination of drive and compactor element was focused. Compressed air purification and downstream applications were not considered.

With the aim of a broad applicability of alternative approaches in an industrial context a pressure in the range of approximately 6 to 12 bar and a supply quantity equivalent to a conventional compressor between 10 and 300 kW should be achieved (Radgen, Blaustein 2001; Ruppelt 2003). Based on this restriction, approaches were not recessed, which did not reach the specified flow rates or pressure levels (for example, piezoelectric compression, sound compression or drag-compression). Furthermore, only plants for central compressed air generation were considered; Approaches of decentralized compressed air production, mobile compressors and approaches with a strong dependence on external influence variables such as the direct production of compressed air by wind and water power were not considered. Even plants that are driven by electricity from renewable sources were not considered here as alternative ways of generating compressed air.

Based on a literature review potential alternative approaches for generating compressed air were identified, which can be subdivided into drive- and compactor-sided concepts. The drive-sided concepts can be attributed to the field of cogeneration (Combined Heat and Power generation or CHP). These concepts include the use of combustion engines (piston engines), micro gas turbines, steam turbines, the Organic Rankine Cycle (ORC), the Kalina process and the Stirling engine. On the compactor side, the concept of adiabatic compressed air and the liquid-based compression were considered.

To ensure a juxtaposition of these different potential alternatives, a total of 14 interviews with experts in the field of *compressed air technology* as well as in the field of *cogeneration* were conducted. Of this total, seven interviews were conducted with experts in the field of *cogeneration* and seven interviews with experts in the field of *compressed air technology*, mostly out of R&D. Furthermore, the interview partners were out of industry (nine experts), associations (two esperts) and science/research (three experts).

The interviews were conducted using an interview guide, where either compressed air technology or cogeneration was discussed, depending of the conversational partner‘s expertise. The interviews lasted between 15 and 50 minutes and were held by phone with two exceptional cases (written feedback). General trends were discussed (depending on the group about compressed air technology or cogeneration) and alternative ways of generating compressed air were assessed. Furthermore, depending on the level of knowledge of the participants, an in-depth examination of selected alternative approaches was performed.

2. Assessments of the dialogue partners

2.1. General developments and trends regarding compressed air generation

At the beginning of the interviews developments and trends in the field of compressed air technology were discussed. For this purpose only experts working in this field were asked. As drivers for the implementation of efficiency-enhancing measures increased an awareness of energy efficiency issues among manufacturers and customers were cited by the most experts. For customers, the motive of reducing energy costs is considered to be very relevant.

In the past years (2002-2012), according to the majority of the experts, in the overall compressed air system an increase of about 5-10 % in energy efficiency was achieved. These savings refer to the entire system including distribution. Some experts argued that an increase in excess of +10 % would have been technically possible; such measures due to the associated costs, however, were not considered further, see figure 1.

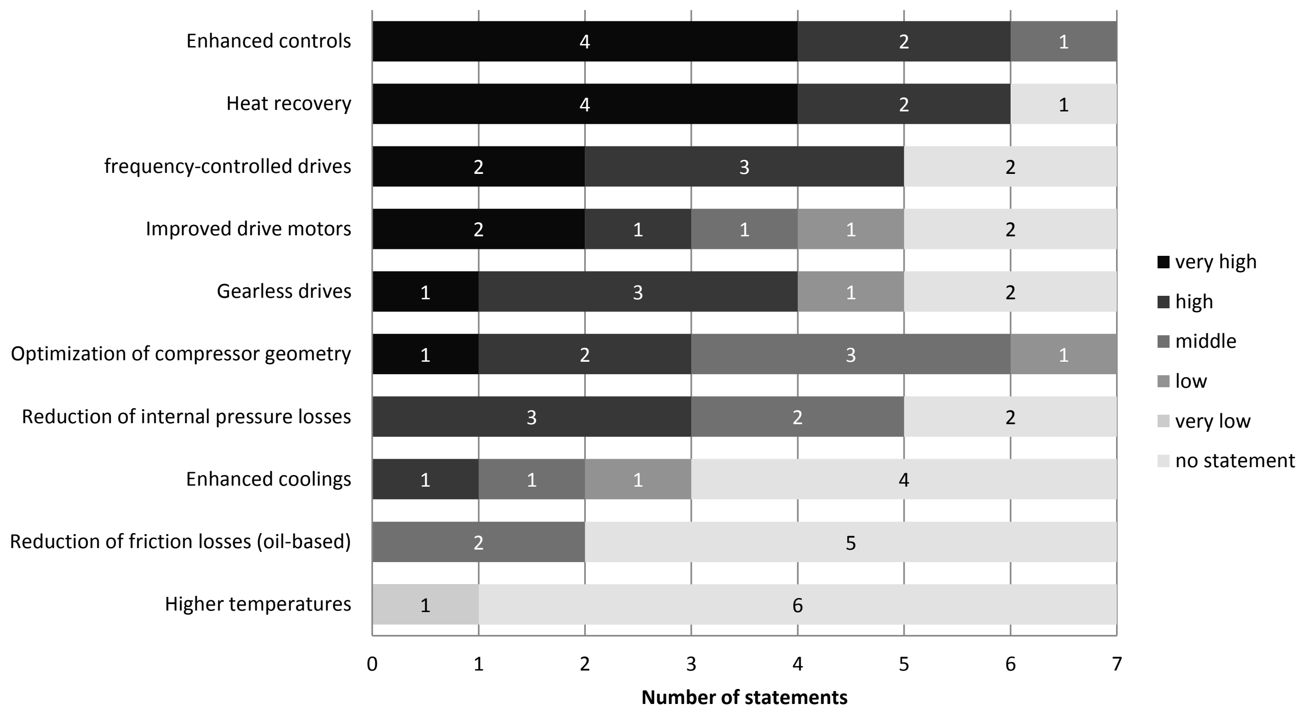

Figure 1: Assessment of the relevance of energy efficiency measurues in compressed air generation in the last years (2002-2012, 7 experts).

In particular, the increased use of higher-level controllers, the use of frequency-controlled drive motors, gearless drives and the increased use of permanent magnet motors instead of asynchronous motors were considered to be very relevant for enhancing energy efficiency.

The opinions of the experts on the relevance of an optimization of compressor geometry scatter significantly. Among other things, a change to higher densification temperatures in dry running compressors was mentioned, but its importance for increasing energy efficiency was considered to be rather low. In addition, the reduction of internal friction losses has been classified as of little significance. Efficiency improvements to compressor stages were achieved only in moderate scale (<< 5 %).

Closely related to compressed air treatment is heat recovery: In the past years (2002-2012), according to the experts, an increased customer's attention and use of heat recovery was observed. In addition to the field of compressed air generation, other, more systemic aspects were mentioned: In compressor stations significant savings could have been achieved by improved ancillary components (e. g. dryers).

Looking at the entire system “leakage minimization” is considered very relevant. The availability of improved measuring devices for the detection of leaks in the pipeline system played a key part in increasing overall efficiency. In addition, a preferably low pressure level, adapted to the application is another important efficiency measure.

None of the experts mentioned completely new drive or compression principles that might be applied broadly in future. Essentially existing systems have been developed further and optimized.

Looking at the development in the next years no radical process changes in the field of compressed air generation are expected by the experts. The focus will be more on the optimization of the overall system, where improvement potential has been estimated at up to 5 %. On the drive side, it is expected that the use of IE-3 electric motors will bring further efficiency improvements. Especially when compressed air consumption varies, quickly reacting drives with long lifetimes are required that are reliable even with frequent warm-ups in start-stop operation. Regarding compressor-side improvements two experts called new coatings and materials for gap reduction in the compressor block to minimize the internal pressure losses, thereby achieving an increase in efficiency. In addition, further improvement through the optimization of ancillary units is seen. For example, improved technologies for the regeneration of dryers will attain increased attention. The field of heat recovery will be of increased improtance also in the next decade. Partialy older compressors can be retrofitted with a heat recovery system. In the near future no radical advancements in the field of compressed air supply are to be expected.

2.2. Assessment of alternative approaches for compressed air generation

2.2.1. General statements of experts in the field of compressed air technology

The majority (> 90 %) of the stationary air compressors used today in industry is driven by electric motors. The fact that this drive type is mainly used is based on the following characteristics of the electric motor (qualitative expert statements):

- High technological level of development,
- high availability of electricity (widespread electricity network),
- high efficiency of motors,
- excellent controllability,
- very low wearing, relatively long life time,
- use of electricity from renewable sources possible.

Other types of drives for compressed air generation are almost exclusively used in special applications, since no other drive concept has such a high degree of flexibility as the electric motor. Alternative compression principles, such as liquid-based compression or the use of adiabatic compressed air would also be used for for special applications only. A compressor manufacturer speaks in the context of alternative options of a possible *renaissance* of the piston compressor, since it would have the best efficienciy.

Concerning the use of combined heat and power plants for compressed air generation experts of two compressor manufacturer answered that such a coupling has been studied but related to the relatively high gas price was not considered further. Herby gas was used to fire piston engines. Also the presence of a relatively large heat sink is necessary in this case; otherwise this concept is not economical. However, another expert reported that this approach would be practiced in the industry and the heat produced could also be used for cooling (absorption and adsorption).

2.2.2. General statements of experts in the field of cogeneration (CHP)

In particular, since CHP systems can be used for generating compressed air, this group of experts was initially asked for a general assessment of the suitability of CHP approaches for the generation of compressed air. These approaches are different from the conventional compressed air generation by the fact that instead of plugging an electric generator to the CHP a compressor is connected and so above mentioned conversion losses are minimized.

The majority of the CHP expert in principle supports the concept of a combined generation of compressed air and heat. Depending on the presence of an appropriately sized heat sink this is also economical. Hereby nearly any fuel type could be used. By the experts the use of a combustion or a Stirling engine is strongly recommended as the most relevant CHP technologies today and also in future (until 2022), see figure 2.

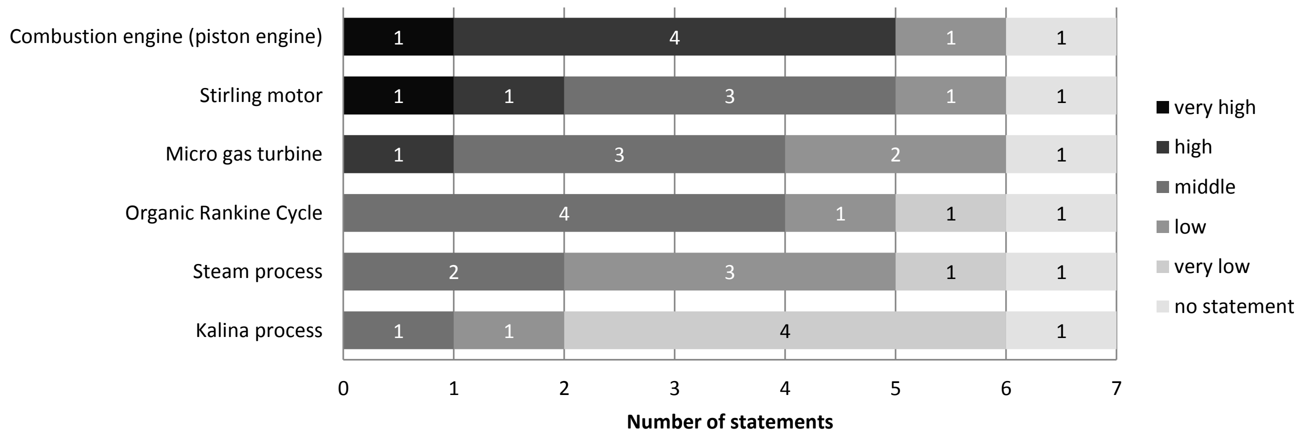

Figure 2: Relevance of drive technologies for use in CHP for producing mainly compressed air (7 experts).

However, it was also noted by the experts that the optimization of the utilization ratio (ratio of usable electricity and heat to the total energy use) would be in the foreground in the next decade; in particular the increase in the degree of utilization by the optimal external use of waste heat. In the case of an intensifying trend towards decentralized energy production, the expansion of a nationwide heat network is conceivable to distribute heat that occurs in the process of electricity or compressed air generation. Additionally, potential improvements have been mentioned by the experts in partial load operation of CHP plants.

2.3. Detailed assessment of chosen concepts

To obtain a detailed assessment of each alternative technology in the course of the interviews in-depth discussions were led. For a structured query of defined individual criteria a 5-point Likert scale was used. The participants were asked to classify the discussed technologies relative to the state of the art; which is the electric motor (drive-side) and the screw compressor (compactor-side). The used criteria refer to a Delphi study on *Future technologies of compressors and vacuum pumps* (VDMA 1997) and were slightly modified for the purpose of this observation, see table 1.

Table 1: Overview of criteria for evaluating alternative technologies relative to the state of the art.

Criterion	Short desctiption and leading question
Energy demand	Energy demand mainly determined by the efficiency *How do you assess the primary energy demand compared to conventional technology (electric motor / screw compressor)?*
Reliability	Functional availability of the technical installation *How do you assess the life / reliability of the technology compared to conventional technology (electric motor / screw compressor)?*
Capital investment	Investment in a new plant *How do you assess the investment compared to the conventional technology (electric motor / screw compressor)?*
Power output range	Conformity of the power range with defined specification *How do you assess the match between the performance area covered by the technology and the required power range (corresponding to a compressor with a power of 10 to 300 kW)?*
Maintenance effort	Effort for the maintenance of the technology *How do you assess the cost of maintenance compared to the conventional technology (electric motor / screw compressor)?*
Noise emission	Noise emission during operation *How do you assess the noise level of the technology compared to the traditional technology (electric motor / screw compressor)?*
Applicability today	Applicability to the current time *How would you rate the applicability of the technology for the generation of compressed air on the state of the art?*
Development prospects	Future development of the technology *How do you assess the potential for further development of the technology for the generation of compressed air?*

In the following sections, each (alternative) compressed air generation technology is briefly described and the assessments of the experts are presented subsequently. The discussion is based on statements of CHP and compressor experts.

2.3.1. Combustion engine (piston engine)

Technological description: The combustion engine is an established drive technology in mobile compressed air applications (for example construction site compressors). This technology is based on the coupling of internal combustion engines (particularly diesel engines) with compressors. As internal combustion engines in most cases oscillating piston machines are used, whose mode of operation is at this point not to be discussed further. They are available in different capacities from a few kilowatts to a few megawatts of mechanical power. With a share of about 66 % they are the primary energy converter in cogeneration up to 300 kW (Schmid 2003).

Expert assessment: The internal combustion engine fuelled with gas (also biogas) has a relatively high potential for operating in a stationary compressed air generator. However, internal combustion engines have, compared to the established electric motor, several drawbacks:

- High effort for maintenance / wearing due to the large number of moving parts and the internal combustion,
- relatively high fuel costs,
- relativly complicated handling (e. g. refueling, lubrifying, …),
- relativly low efficiency in the considered performance class,
- production of local emissions (air pollutants, greenhouse gases, e. g. CO_2),
- necessity of compliance with emission regulations,
- mineral oil tax accrues.

Because of these limitations, the engine currently is only used in compressors where no electric power supply is available.

During the expert discussions with respect to individual criteria it shows that the internal combustion engine due to its mature technology and due to its availability an applicability higher than average is awarded as an alternative technology for generating compressed air, see figure 3. Also, the power range is classified as very high to high in the context of industrial compressed air generation. The opportunities for development of the engine generally are in a mid to very small rating, as this technology has already been developed for many years and therefore no significant innovative improvements are expected. Regarding the maintenance costs and the reliability of this drive concept, the statements of the experts vary widely. This can be explained by the fact that some experts considered the base load case in which the engine is used in continuous operation with just a few starts and stops. In this case, the concept is awarded a relatively high reliability. However, if load fluctuations are to be compensated for example by frequent starting of the engine, it reduces the service life of the engine significantly.

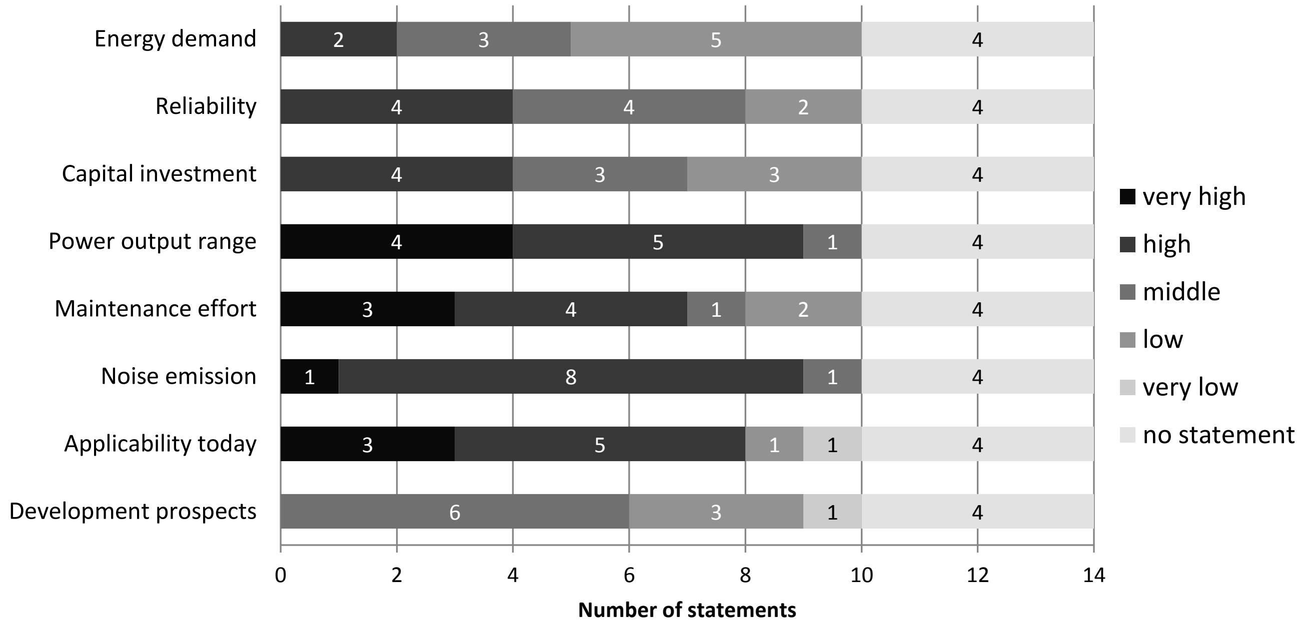

Figure 3: Detailed analysis of the combustion engine (piston engine) with respect to selected criteria.

2.3.2. Micro gas turbine

Technological description: Gas turbines are mainly used when powers of several megawatts are required. Most gas turbines for mechanical drives have a performance range of 30 MW up to 129 MW and achieve efficiencies of up to 38.5 % (Lechner, Seume 2010). Compressors and pumps are driven by gas turbines in parts of the oil and gas industry (Kolev et al. 2000). In the relevant power range for the generation of compressed air of up to 300 kW so called micro gas turbines are used, which are however characterized by a relatively low efficiency of up to 30 % (Kong et al. 2004: Lechner, Seume 2010; Peche et al. 2007). However, Thomas (2007) mentions the use of micro gas turbines as CHP technology in CHP plants of 28 kW electrical power.

Expert assessment: Micro gas turbines have a power range between 10 kW and 300 kW and a comparatively low efficiency, since, according to the experts, high gap losses occur. The larger the gas turbine is dimensioned, the smaller is the relative impact of these gap losses. Another reason for the low efficiency of the micro gas turbine is the relatively high exhaust gas temperatures. Because of the gap losses it is advisable to use gas turbines of more than 500 kW. Furthermore, it was noted by the experts that micro gas turbines in start / stop operation have a very high wear and thus high maintenance costs. If the turbines were used in base load and continuous operation the maintenance effort would decrease significantly. The availability of natural gas, the taxes involved and the occurence of air pollutants and greenhouse gases (e. g. carbon dioxide) are other aspects that would speak against a widespread use of this technology in the field of compressed air production.

The use of a micro gas turbine in connection with a turbo compressor in base load operation in the presence of an appropriately dimensioned heat sink (CHP) is quite conceivable, also because the rotation speed doesn't need to be transformed (e. g. using a gear box). It should be noted that a turbo compressor compared to a screw or piston compressor delivers a relatively high flow rate (> 140 m³ / min). Thus, the delivery quantity for the most industrial cases is relatively high and also above the power range previously defined.

Furthermore, it was noted by an expert, that the use of micro turbines currently is mainly confined to areas without electrical supply for example to drive decentralized power generators. Under consideration of the defined criteria, a very high capital investment is obvious, see figure 4. When driving a turbo compressor by a micro turbine in base load (continuous operation) a very high to high system reliability and a medium to low maintenance effort is assumed. The power range of available micro turbines is relevant for industrial compressed air production. Regarding the applicability for generating compressed air a highly differentiated picture shows up. This is due to the fact that some experts have primarily considered the application in conjunction with turbo compressors. In this regard, the low mechanical efficiency and significantly high exhaust gas temperatures were mainly mentioned during the interviews. This is reflected by a medium to high energy demand for the actual generation of compressed air. The development potential of the technology, also in terms of efficiency, was assessed as very high to high by the experts.

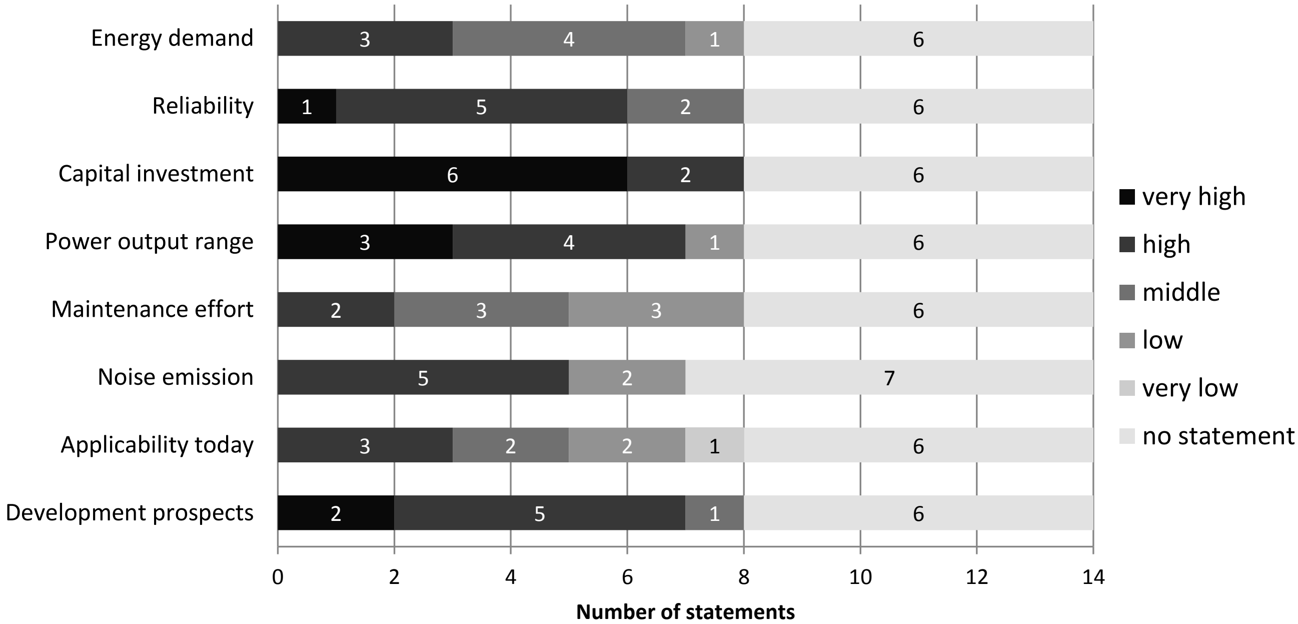

Figure 4: Detailed analysis of the micro gas turbine with respect to selected criteria.

2.3.3. Rankine Cycle (steam cycle)

Technological description: When operating a process using the Rankine Cycle (steam cycle) solid, liquid or gaseous fuels are burned in a boiler and the generated heat is used to warm up a working fluid (steam generator). The resulting (water) vapor drives a steam turbine (Fuchsner et al. 2010; Strauss 2010). The turbine can be coupled with a compressor for generating compressed air. One steam turbine connected to a compressor can be found in a pilot plant in southern Germany. This system provides a flow rate of 33 m³ / min at a pressure of up to 8 bar. The structure is set up by a single-stage backpressure steam turbine, which is coupled without a gearbox directly to a screw compressor. This compressor is used as a base load machine. For peak loads other, conventional electrically driven compressors can be attached to the system (Bierbaum 2000).

Expert assessment: The generation of steam to drive a compressor is considered uneconomical due to the relatively low efficiency in the power range between 10 kW and 300 kW and the high technological complexity. However, if an existing steam network could be used, e. g. in the chemical industry, this form of driving a compressor is considered as quite economical and practical. According to one single expert some pilot plants already exist. Since steam turbines are characterized by complex control mechanisms (compared to the electric motor) and have relatively long start-up times, the operation is considered as practicable in the base load only.

When considering the criterion “energy demand” an inhomogeneous picture shows, see figure 5. This could be because some experts have not included the generation of drive energy from a primary energy source in their considerations. This assumption would also explain the relatively large differences in the ratings for criterion "applicability today". As several pilot plants already exist, the power range is estimated to be very high to high. The maintenance effort is considered to be very low with this technology because of the low wear of moving parts. Investments are considered as very high to high.

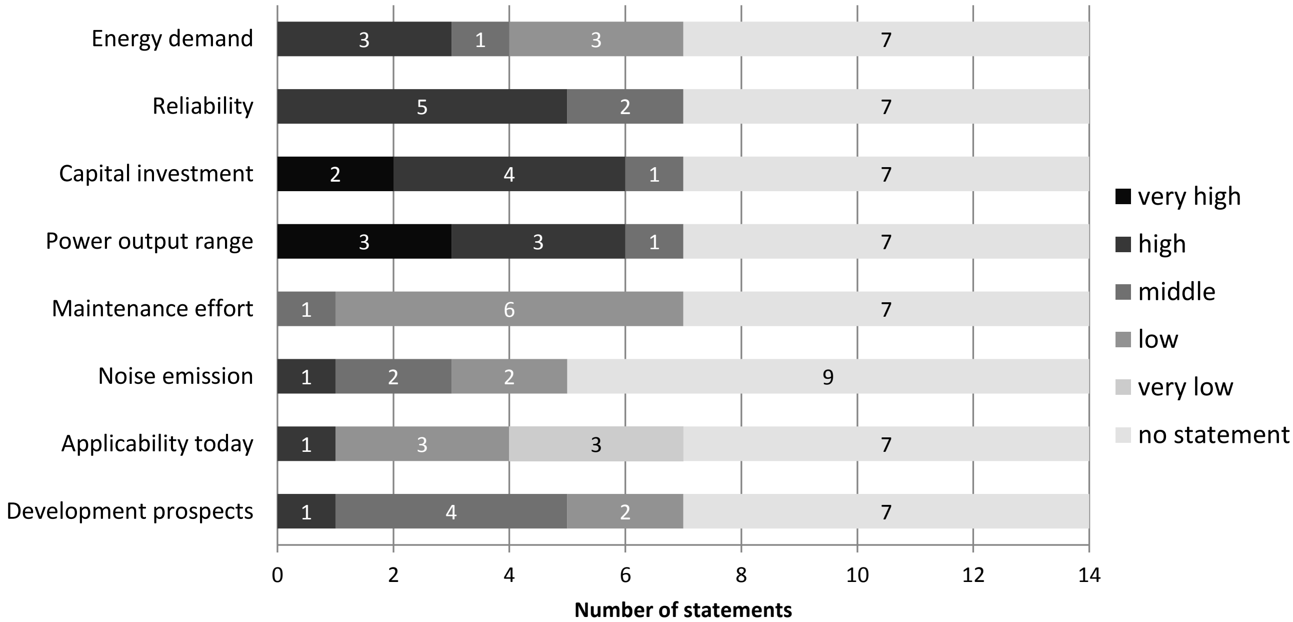

Figure 5: Detailed analysis of the Rankine cycle (steam cycle) with respect to selected criteria.

2.3.4. Organic Rankine Cycle (ORC)

Technological description: The Organic Rankine Cycle is a vapour process similar to the steam process described above. In Organic Rankine processes as working fluid no water circulates but an organic substance, usually a so-called refrigerant (R-12, R-123, R-134a or R-717) (Roy et al. 2011). These substances boil at much lower temperatures and pressures than water. Turbines based on the principle of ORC are partially used in cogeneration systems, in which about 120-2,000 kW total power can be yielded (Thomas 2005).

Expert assessment: It was emphasized by the experts that the ORC process has a very low efficiency (< 15 %) in the considered power range and that it is characterized by a very high technological complexity. The refrigerants used in the cyclic process are mostly chlorofluorocarbon, which are classified as critical substances by the experts. In electric power generation, the ORC process is gaining importance, especially in the conversion of biomass in a low temperature range. It can be used already at a much lower temperature level compared to the conventional Rankine Cycle (depending on the organic substance between 100° C and 350° C).

It was noted by some experts that a relatively high amount of energy is required for the generation of mechanical drive energy due to the low efficiency of the underlying thermodynamic cycle, see figure 6. Using this technology also no internal combustion takes place, thus a high reliability and relatively low maintenance costs are mentioned by the experts. The investments are estimated as to be pretty high. This is on the one hand determined by the very high level of technological complexity of the plants and the currently low market diffusion. The applicability in the range between 10 and 300 kW is considered to be very low. However, at the same time it has been rated with a high development potential. In the analysis it is important to note that only three experts could discuss this approach.

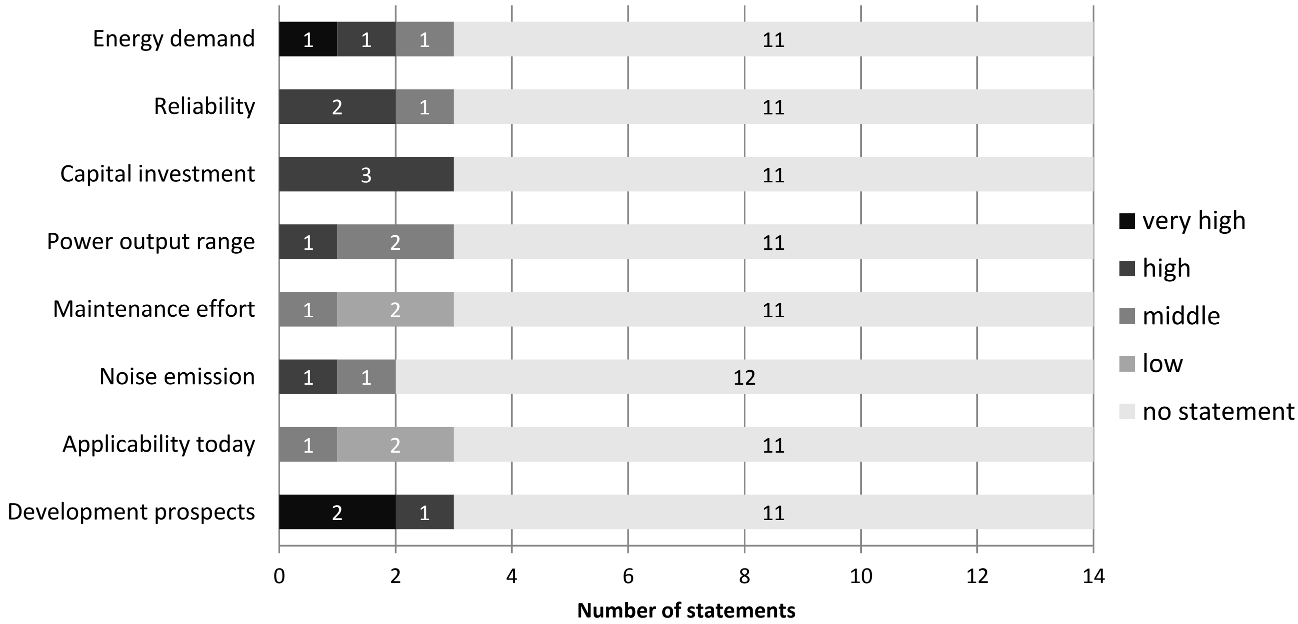

Figure 6: Detailed analysis of the Organic Rankine Cycle (ORC) with respect to selected criteria.

2.3.5. Kalina process

Technological description: The Kalina cycle is a vapour process similar to the Rankine process described above. In this case a mixture of ammonia and water (NH_3 + H_2O) is used as the working medium. In the Kalina cycle, the working medium does not have a fixed boiling point, an adjustment to the thermal conditions at the operation site can be accomplished by varying the ammonia / water ratio (Piacentini 2005). The Kalina cycle is able to deliver a 10-20 % higher thermodynamic efficiency than the Rankine cycle in the same temperature range (El-Sayed and Tribus 1985). Kalina installations are mainly used because of their lower temperature levels in geothermal and waste heat recovery (Fuchsner et al. 2010). According to a study efficiencies between 12.3 % and 17.1 % with a thermal input power of 2.3 MW could be achieved (Ogriseck 2009).

Expert assessment: Due to the weak distribution of the technology, none of the experts was able to assess the Kalina process as a driving concept for compressed air generators. Thus it is not considered further.

2.3.6. Stirling engine

Technological description: A thermal process combination for the generation of compressed air and heat is the coupling of the Stirling engine with a compressor. Here nearly all types of fuel can be incinerated or a waste heat source can be used. The Stirling engine is a heat engine based on the Stirling cycle and usually is implemented by two moving piston in a cylinder. They are exposed to a temperature gradient. The Stirling engine converts thermal energy without internal combustion directly into mechanical energy and therefore has a relatively simple, compact design. With a connected compressor the mechanical energy can be used to generate compressed air.

Expert assessment: According to the estimates of individual CHP experts the Stirling engine is the most relevant drive alternative to the internal combustion engine, in particular due to the variety of fuels that can be used (e. g. woodchips, biogas). Furthermore, this drive concept due to its simplicity is characterized by a low maintenance effort and a high reliability. However, the mechanical efficiency in the considered power range is comparatively low. Therefore an adequately dimensioned heat sink must be present when used in cogeneration mode. If this heat sink is available, according to statements of some CHP experts, the use of the Stirling engine for generating compressed air is regarded as being suitable. As a disadvantage of this drive concept experts still mention the need for relatively high capital investments.

Particularly striking in the detailed review are the high reliability and the low maintenance efforts of the Stirling engine, see figure 7. This is due to the relatively simple construction of the engine and the outer combustion. This technology has, compared to the other concepts, the highest progression potential. In particular, the increase in efficiency by a further approximation to the thermodynamic optimum is possible. In ten years Stirling engines could have higher efficiencies than comparable-sized diesel engines (according to a statement of an expert on Stirling engines). For power ranges above 10 kW, the mechanical efficiency then would be at approximately 50 %. It should be noted that assessments of manufacturers of this technology are significantly more optimistic than the statements of experts out of other fields (research and associations).

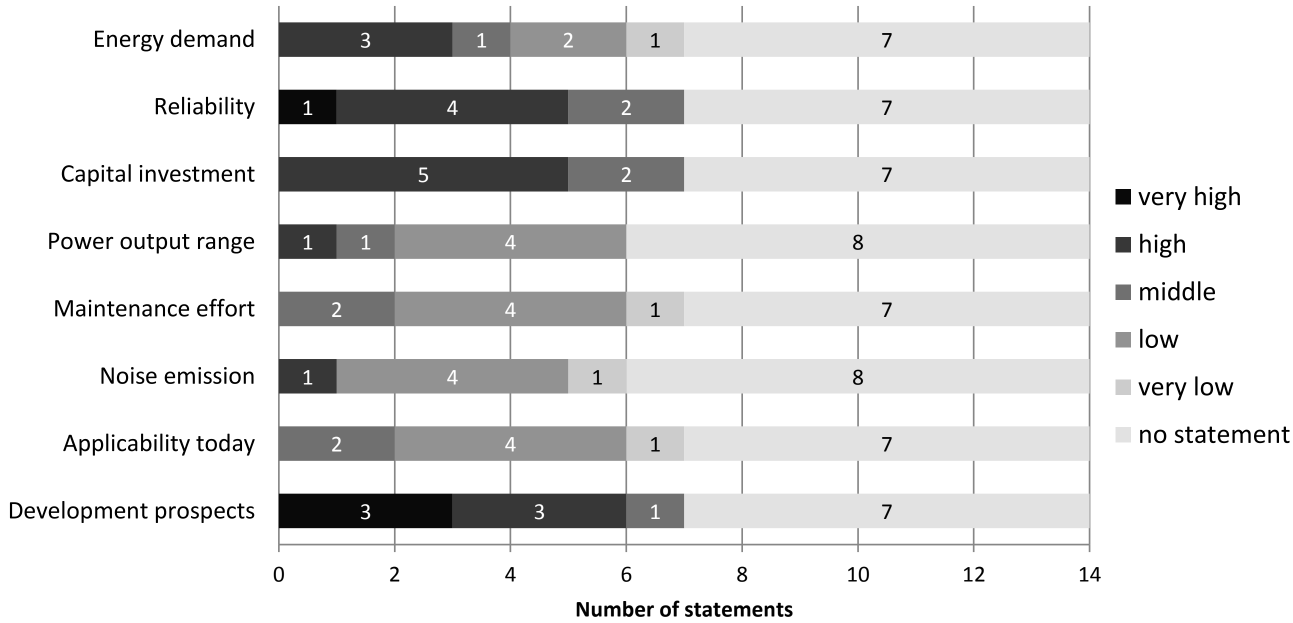

Figure 7: Detailed analysis of the Stirling engine with respect to selected criteria.

2.3.7. Adiabatic compressed air

Technological description: The use of adiabatic compressed air strictly speaking is no alternative generation approach for compressed air. It is, however, closely related to the generation of compressed air and therefore is also considered here. The approach is based on the utilization of the heat produced during the compression in the form of an increase in pressure of the compressed air. To use this adiabatic compressed air it must not be cooled during compression (or only at critical points). In this case, the compressed air due to the higher energy level has a higher pressure as well. Thus, the efficiency of the compressed air supply theoretically increases. After adiabatic compression, the effluent air has very high temperatures (depending on the compression ratio and the introduced power). Bloch (2006) speaks of temperatures of up to 250° C with typical screw compressors. Barth (2000) noted a resulting temperature at a compression from 1 bar to 10 bar of about 300° C. The higher pressure, however, is usable only in the time window, in which the elevated temperature of the compressed air persists. The air should therefore immediately be placed in insulated piping and distributed to nearby applications to avoid cooling and thus a pressure reduction (Barth 2000).

Expert assessment: When using hot compressed air the possibility of component failure exits because some system components are not designed for temperatures of approximately 250° C (in some cases even higher). The maintenance effort for the entire compressed air system and the associated costs would rise significantly in this case. This also has a negative impact on system reliability. This form of compressed air is used in practice only in special cases, if the temperature of the air is of subordinate interest. The use in areas, in which compressed air is required for various processes, e. g. in the chemical industry or in the steel industry, might be considered. Here people would not come into contact with the hot compressed air. The use of hot compressed air in a common industrial context is considered as not being practical because of the aforementioned limitations.

Only two experts have given a more detailed assessment of this concept, see figure 8. The majority of the CHP experts didn’t know about this concept. Nevertheless considering these two reviews, a homogenous picture shows: The energy demand is considered low, as the reliability, since there may occur the above mentioned component-damaging effects of hot air. The applicability is severely restricted, since this concept can’t be applied when people work with the generated compressed air. This approach shows the least development prospects in a common industrial context, as mentioned disadvantages significantly limit the applicability also in the future. Investments are however considered low, since the only difference to the conventional compressor design is to omit the cooler.

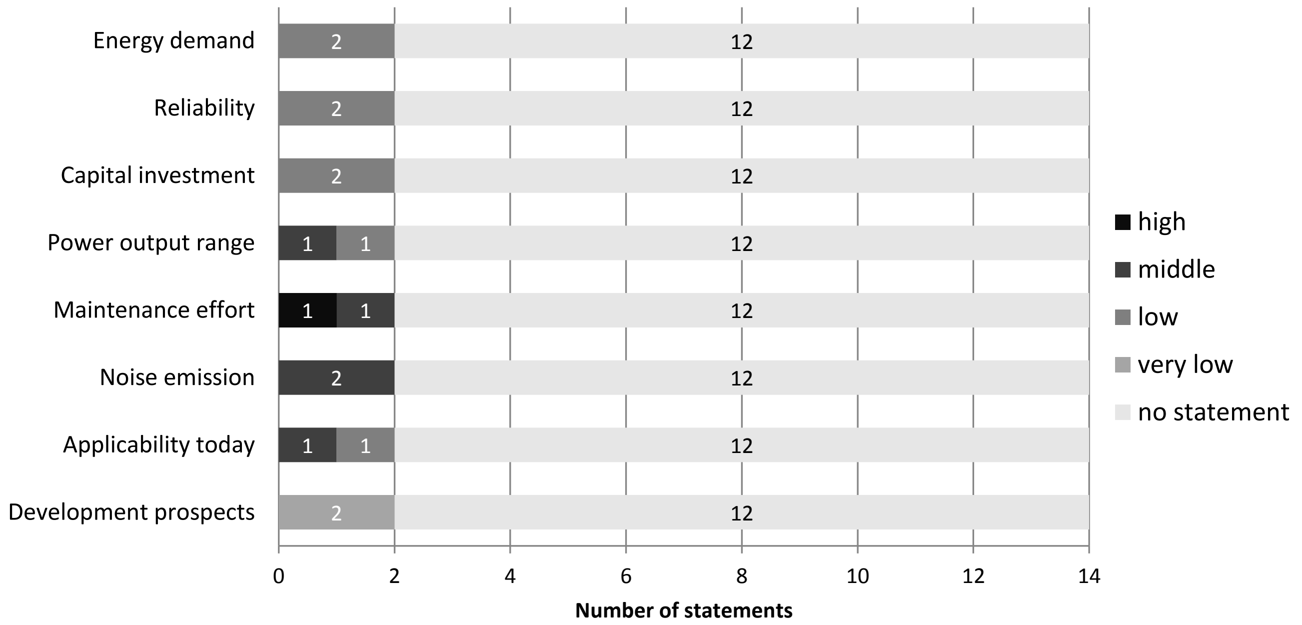

Figure 8: Detailed analysis of the use of adiabatic compressed air with respect to selected criteria.

2.3.8. Liquid-based compression

Technological description: In order to achieve a process which comes close to an isothermal compression, it is conceivable to employ a reciprocating compressor that uses a liquid column (ionic liquid) instead of the metallic piston, and is operated by a hydraulic pump (Linde AG 2006; Brückmann and Cyphelly 2007; Van de Ven and Li 2009). The compression process is accomplished by various valve-controlled fluid cylinders which are alternately filled and emptied with the ionic liquid. The necessary volume flow of the working fluid is provided by an electrically driven hydraulic pump. Such compressors are also referred to as ionic compressors.

Expert assessment: This approach is characterized by very low maintenance efforts and a high reliability of the equipment. The number of moving parts is minimal. However, the circulating ionic liquid is subject to aging effects, due to the fact that dirt particles from the gas to be compressed are included. Ionic compressors are usually used at high pressure (> 250 bar) to liquefy gases, mainly hydrogen and natural gas. In the pressure range of 250 bar to about 1,000 bar energy savings of up to 20 % could be achieved (compared to conventional compression). Among other things, this is achieved through improved heat dissipation, tightness of the compressor and low friction of the "hydraulic piston rods". In the standard pressure range the use of ionic compression however is not recommended by the experts.

Significant is the low to very low rating in the criterion "power output range" and the low or very low applicability, see figure 9. The development prospects were estimated in average as high as this technology, in relation to the generation of compressed air, shows the need for further research and shows potential for improvement. In such a compressor design, the number of moving parts is very low compared to conventional piston compressors. Thus this approach is considered to have a very high or high reliability and shows a very low demand for maintenance. The reliability of such systems is largely determined by the quality of the hydraulic pumps used. The energy demand has been classified as medium to high, because the energetic advantages of this technology come to bear only at high pressures. It should be noted that for this compactor-side approach, the experts in the field of cogeneration technologies were not able to give any assessment.

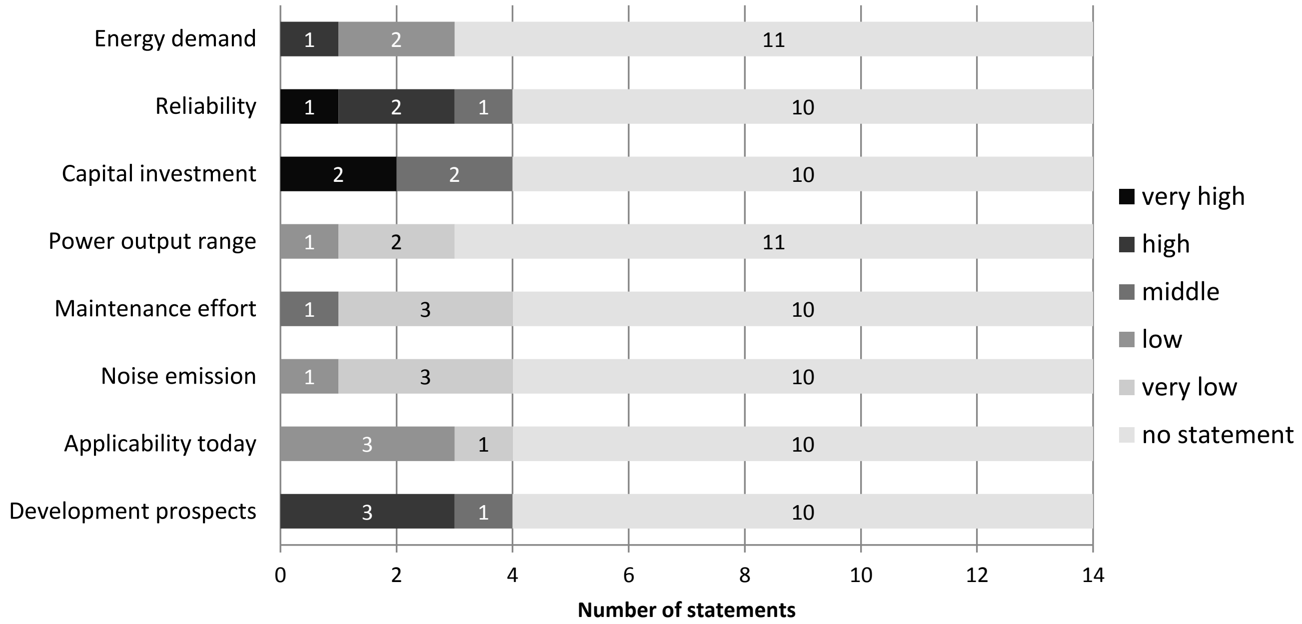

Figure 9: Detailed analysis of the liquid-based compression technology with respect to selected criteria.

3. Discussion and summary

The expert interviews were carried out to identify past developments and future trends in the field of industrial compressed air generation. Further an overview of possible alternative approaches to the generation of industrial compressed air could be gained and were discussed for their potential applicability.

When interpreting the statements, a number of uncertainties are to be noted. In addition to potential distortions created by the selection of the experts, the size of the sample and fuzziness of the information it can be noted, that not all experts could discuss each concept. Further, interviewed manufacturers of specific technologies (e. g. sterling motors) gave more optimistic assessments about 'their' specific technology than other experts. Nevertheless, by the choice of the experts an attempt was made to obtain a broad perspective on the subject.

The results of the discussions show that to date industrial compressed air, depending on the scope of the company's own needs, is generated mainly by electrically driven piston, screw and turbo compressors. Particularly, it appears that future potentials are seen mainly in the optimization of existing technologies and the aspect of optimal system integration. The experts see further efficiency potential through the optimization of the entire compressed air system, including all components (e. g. cooler, dryer, heat exchanger, compressed air storage and distribution) as well as the needs-based control of these systems with enhanced higher management and control systems.

Based on the estimates of the experts it can be concluded that the conventional form of compressed air production represented by electric drive and piston, screw or turbo compressors will remain the most important technology also in the future.

The detailed consideration of each alternative technology shows that in particular the internal combustion engine enables a reduction of energy converstion stages and thus can be seen as an alternative compressed air generation technology. However, compared to the electric motor some restrictions apply (e. g. relatively high maintenance costs, emissions, relatively high fuel costs, ...). High development potential for alternative drive concepts of compressors are seen by the experts in particular in microturbines, the ORC process and the Stirling engine.

Furthermore, it was often noted by the experts that some alternative technologies are usefully employed only in special cases or under specific conditions and therefore appear to be limited for broad industrial use. The use of cogeneration technologies is useful only if the considerable excess heat can also be used or distributed further. The alternative compression principles *liquid-based compression* and the management concept *adiabatic compressed air* are regarded as less suitable for a widespread use.

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