PEC624: M.Sc. Dissertation

Do Hybrid Compressed Air Energy Storage (HCAES) Systems Offer a Viable Alternative Solution to Energy Storage Requirements for Small to Medium Size Renewable Energy Systems?

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A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science in Renewable Energy, Murdoch University.

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Declaration of originality

This is to certify that the work is entirely my own and not of any other person, unless explicitly acknowledged (including citation of published and unpublished sources). The work has not previously been submitted in any form to the Murdoch University or to any other institution for assessment or for any other purpose.

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Abstract

With the increased international pressure to make use of more renewable energy technologies, the intermittent nature of renewable resources requires some kind of energy storage in order to ensure energy is available when needed. Most conventional storage solutions for small to medium size applications are based on chemical batteries which are hazardous, not easily recycled and can have a negative environmental effect. Thus renewed interest is being given to clean and environmentally friendly storage technologies such as compressed air, a technology more than a century old, and still being used in flammable and explosive industrial environments.

New, improved compressors, air motors and advanced technologies and materials that can withstand large fluctuations in temperature have become available, and have been used by some innovative manufacturers to produce Hybrid Compressed Air Energy Storage (HCAES) Systems, which claim to have high turn around efficiencies. In this research, the available literature on compressed air systems, and new HCAES systems are evaluated in order to compare them to conventional storage technologies. Furthermore, an evaluation was conducted to determine if it would be possible to design a HCAES system with off the shelf air equipment and if this HCAES system could possibly be a viable alternative to conventional or new chemical battery storage technologies.

During the research it was found that there is very little literature on the subject of HCEAS systems, and that the manufacturers do not give much information or proof on actual efficiencies of their systems. What was found is that there are several academic institutions working on combining compressed air with technologies such as diesel engines, oil pneumatics, wind, water, super capacitors and flywheels in order to improve current hybrid systems' effectiveness and efficiency in energy storage and supply applications and to reduce the environmental footprint of such systems.

From literature, research and manufacturer specifications it was found that although theoretical efficiencies of close to 100% can be realised, available HCAES systems do

not offer such an effective or efficient solution as chemical battery systems. In addition off the shelf compressors and motors that can be used to design a HCAES system have been manufactured to give high performance and torque with low efficiencies. The efficiency is further drastically reduced as the storage pressure is increased, which is necessary to decrease storage vessel requirements.

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Then a special thanks to two of my colleagues, Michelle Redelinghuys and Paul Davel, both chief engineers, who helped to improve this document by making suggestions regarding its content, style and grammar to ensure that this work is of acceptable standard and quality. Another colleague who made it possible was Jakes Thompson, a DC specialist, who in his hectic schedule provided the DC back-up specifications of Brakfontein repeater station.

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CHAPTER 1

INTRODUCTION

1.1: Compressed Air Background

Compressed Air Energy Storage (CAES) refers to a method used to store energy for later use, by compression and storage of air. Due to the increasing use of renewable energy (RE) technologies, and the intermittent nature of the energy sources that these technologies are based on, energy storage has become one of the main challenges that needed to be resolved in order to improve the reliability and acceptance of the renewable technologies.

For small, remote applications chemical battery storage systems are used in all but a few research installations which utilise experimental technologies such as hydrogen storage. Large, grid-connected peak storage applications have to date been based on Hydro Pump Storage Systems. There are also two CAES systems in operation: one in Huntorf, in Bremen, Germany, which was built in 1978, and the other, McIntosh plant in Alabama, U.S.A., built in 1991. Due to limited locations available for Hydro Pump Storage systems, CAES systems are gaining more attention as a way to address the challenges experienced with the variable nature of wind.

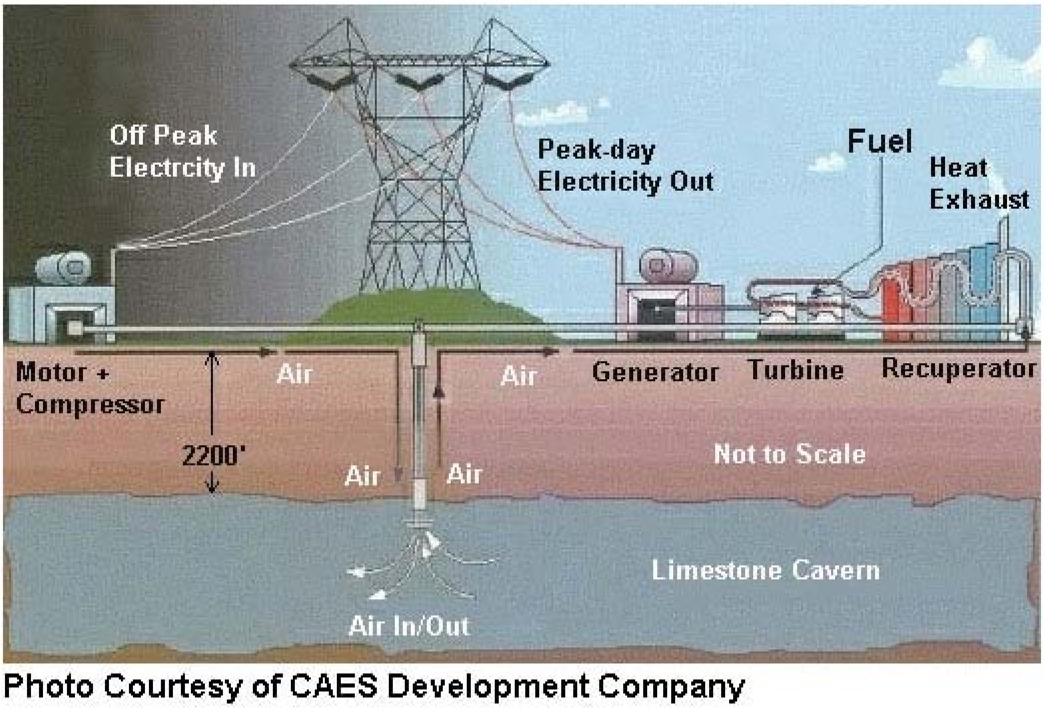


Figure 2: Conceptual representation of CAES (source: http://www.caes.net/)

Increased attention and research are being focused on compressed air technology in order to replace chemical batteries for smaller energy storage applications. Some of the commercial products that are currently available are the thermal and compressed air storage (TACAS) system and the Motor Development International (MDI) generator unit. The TACAS system is an 80 kW uninterrupted power supply (UPS) which can deliver 80 kW for 15 minutes. It is a combination of air, thermal storage and a flywheel. It requires 20 m^3 of air a minute or 300 m^3 for 15 minutes.

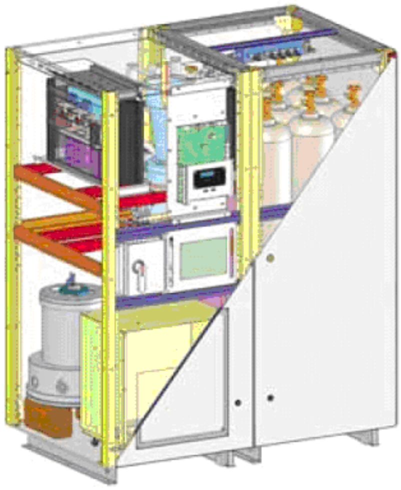


Figure 3: Thermal and Air Storage System (source: http://www.activepower.com).

The MDI technology is based on an air motor invented by Guy Negre of MDI. The technology is based on mono-energy engines operating on compressed air stored at high pressure. This technology is used in prototype vehicles, backup generators and industrial tractors. Unfortunately there is not much information available from the website or research on this technology. Several attempts were made to contact manufacturer for information on the system, without success.

Figure 4: MDI Backup Generator (source: http://www.mdi.lu/english/autres.php).

1.2: Study Area

In order to identify actual sizing of an energy backup system, local applications used in South Africa's Eskom utility were evaluated and after deliberation it was decided to select a radio repeater station. Communication repeater towers all have associated back-up power systems, and in many instances in South Africa and Australia they are located in very remote regions. The Brakfontein repeater station was selected as being representative of a typical Eskom installation and it will serve as the basis for further investigation.

Communication repeater stations receive and transmit data through radio, telephone links and microwaves and serve an important function in the control, monitoring and protection of power systems. To ensure the security of the power system adequate standby power is essential and Eskom specifications require a minimum standby power supply of 12 hours for each station, with full redundancy. Thus translates into each station having a (main back-up) power system able to supply the full power to the station for 12 hours and a main 2 system also able to supply the station for (12) twelve hours. If both systems are intact the station will have a back-up capability of 24 hours. For the purpose of this paper only the standby capacity of one system will be used as reference for comparison to an alternative energy storage system.

1.3: Dissertation Structure

In chapter 2 a review of some of the literature that was found during research is presented in order to evaluate its relevancy to the research question and objectives. Some interesting work has and is being done on compressed air technology, and it shows that increased attention is being focused on developing cleaner energy storage and supply systems using compressed air. There is a strong indication that the advent of the air powered car could have been the catalyst for this renewed interest.

Chapter 3 describes the evaluation of current commercially installed battery systems with an overview and comparison of the TACAS HCAES standby system. The discussion also includes data on the local application indicated above, which will be used to give a credible idea of the energy storage requirements in a practical application. Finally, the chapter describes the available equipment that could be used to design an off-the-shelf HCAES system.

Chapter 4 includes the analysis and results of efficiency calculations on a practical CAES design, based on information from air equipment manufacturers' specification sheets. The analysis and findings are then discussed in Chapter 5, with conclusions and recommendations in Chapter 6.

1.4: Aim and Objectives

Energy storage is one of the main challenges to overcome in order to support renewable energy technology due to the intermittent nature of the majority of primary renewable energy sources. There is an ongoing research on these energy storage systems to improve their efficiencies, energy storage capacity and density.

"Energy storage in a power system can be defined as any installation or method, usually subject to independent control, with the help of which it is possible to store energy, generated in a power system, keep it stored and use it in the power system when necessary (source: Energy Storage for Power Systems, A. Ter-Gazian and Pieter Peregrinus, 1994).

There is a lot of ongoing work and research being done in comparing energy storage technologies. Each technology has inherent advantages, disadvantages and limitations. Well known technologies, such as different chemical batteries, hydro pumped storage and to some extent compressed air energy storage are used within the power industry. Newer technologies such as flow batteries, flywheels, super capacitors, super conducting magnetic energy storage, hydrogen energy storage and thermal energy storage are being introduced into the market as they become more viable arising from advances in technology, cost and political pressures.

Within the energy storage research increased attention is being applied to a technology based on compressed air energy storage for smaller energy storage applications, such as stand-by generation and uninterrupted power supplies. From the research literature found, there is a strong suggestion that renewed interest has originated from research and development of air powered cars, which has driven advances in technology that led to development of more efficient air compressors and motors. This technology, unlike the existing CAES technology which still utilises fuel in the power generation cycle, combines other technologies such as flywheels, super capacitors and heat storage to improve efficiencies and overcome some of the disadvantages and limitations of the existing commercially available systems. The combination of technologies can be seen as a hybrid of different energy storage technologies, and is therefore called a Hybrid Compressed Air Energy Storage System (HCAES). Due to the fact that it has only been introduced very recently, there is very little comparative data with regard to conventional energy storage technologies.

Therefore, in order to evaluate whether a HCAES system could offer a viable alternative solution to the energy storage requirements of small to medium sized renewable energy systems, the following objectives were set in order to provide sufficient evidence to either support or refute the research question:

- Research and report on available air energy storage and delivery methods.
- Understand challenges of utilising compressed air as the energy storage medium.
- Understand theoretical and practical implications of the thermodynamics of compressed air systems.
- Evaluate existing or experimental HCAES technologies in order to identify the most practical technologies that could be used to develop a locally produced HCAES system.
- Gather and analyse data on the energy storage requirements of a selected local application requiring a back-up power supply system.
- Use the data and the identified compressed air technology to design a HCAES system.
- Compare the HCAES design with the existing back-up system.

- Compare costs associated with both installations. (This relates to the viability aspect).

From the above objectives some literature study was required in order to find the most relevant information available that would support or refute the main research question or could serve as guidance on how to design a HCAES system that could be used to replace conventional chemical batteries.

CHAPTER 2

LITERATURE REVIEW

2.1: Introduction

In order to better understand contemporary HCAES technology and research it was important to perform a literature review of existing papers, books and other research material. The largest information resource available was the internet, with a few selected textbooks on energy storage available in academic and utility libraries. The information found on the internet on the topic of HCAES was limited and mostly based on ongoing research, with some researchers advertising HCAES technology for UPS and standby power generation applications, making claims of high turn around efficiencies without offering credible supporting evidence.

2.2: Compressed Air Research

Principle of Hybrid Energy Storage Systems based on Hydro-pneumatics and Super-capacitors for Distributed Generation and Renewable Energy Sources support. Written by S. Lemofouet and A. Rufer. Industrial Electronics Laboratory (LEI) - Swiss Federal Institute of Technology (EPFL). 2005. Accessed: 20 June 2009. Webpage: leiwww.epfl.ch/publications/lemofouet_rufer_eesat_05.pdf

The paper by Lemofouet and Rufer explains the functioning of a very innovative energy storage system based on hydro-pneumatics and super-capacitors, and compares the cost of the system to tubular lead acid battery system. It is interesting to note that compression and decompression is achieved using liquid cylinders (oil) and is called the “Batteries with Oil-hydraulics and Pneumatics (BOP)” system. The paper describes two systems, the BOP-A which was lab tested and proved the fundamental principles, and the BOP-B system where compression and expansion of fresh air is done in liquid piston work chambers with integrated heat exchangers. The authors claim that by using the liquid pistons an almost ideal isothermal process is achieved which will ensure high conversion efficiency and energy storage density. Additionally, they claim a considerable total lifetime cost reduction of the BOP-B system compared to tubular lead acid batteries, for systems above approximately 80 kW storage capacities.

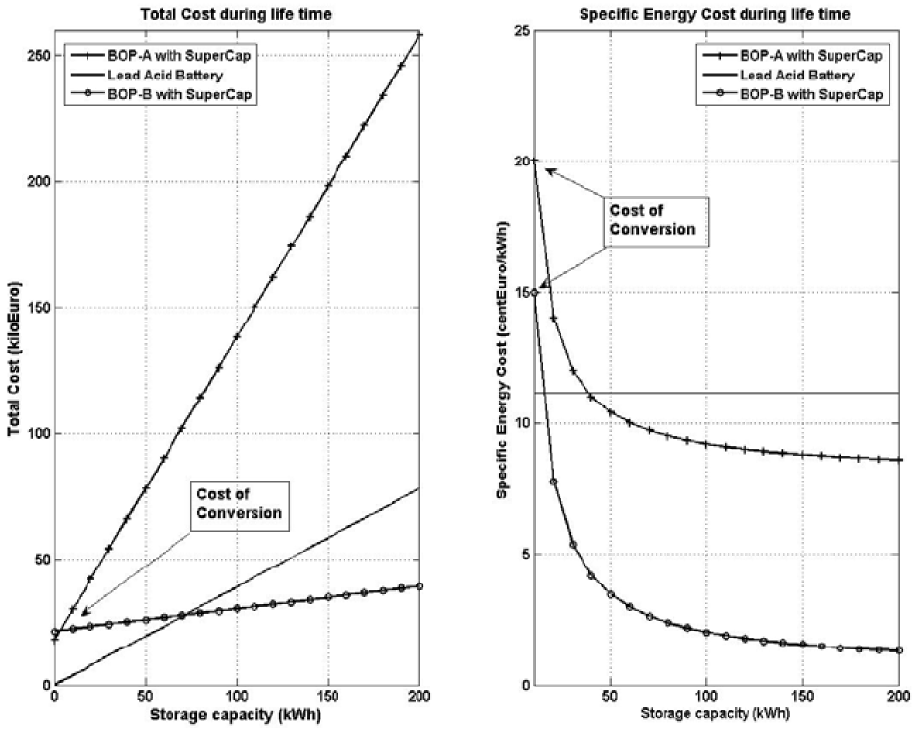


Figure 5: Total cost and specific energy cost versus storage capacity, for a minimum life requirement of 3 500 cycles (S. Lemofouet and A. Rufer, 2005).

The work described on the BOP system opens a range of new applications for a combination of CAS and pneumatics. This research gives a strong indication that high efficiencies are possible for a HCAES system. Unfortunately, it appears as if a great deal of research and testing needs to be done to make this a workable solution to the energy storage problem, and not all the required equipment can be bought off the shelf, which makes this method of storage unsuitable for this dissertation. [by S. Lemofouet and A. Rufer, 2005].

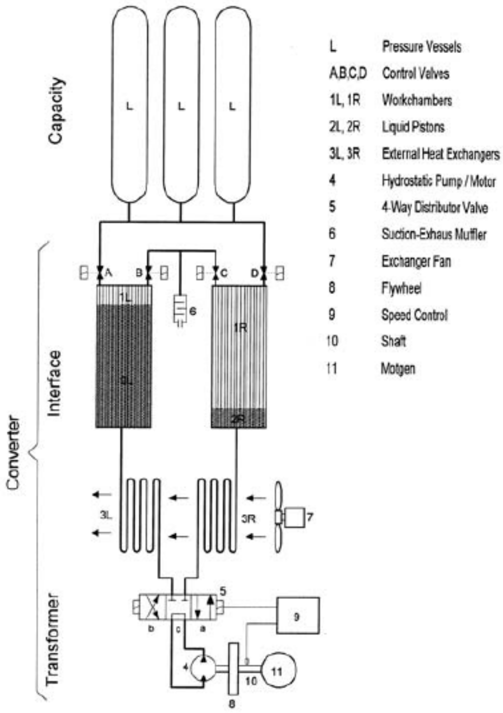


Figure 6: BOP-B Working Principal (S. Lemofouet and A. Rufer, 2005)

Study of a Hybrid Wind-Diesel System with Compressed Air Energy Storage. Written by Hussein Ibrahim *et al*. 25 October 2007. IEEE. Electrical Power Conference 2007. Accessed: 21 June 2009. Webpage: www.ryounes.net/publications/IEEE2006.pdf

The collaboration in writing this paper by authors from Quebec Universities of Rimouski and Chicoutimi, and the Lebanon University of Beirut covered a very interesting addition to the application of CAES technology. The paper looked at the wind-diesel hybrid systems that are currently in use in remote locations in Canada, and how the penetration of wind on these systems can be increased without jeopardising the stability of the diesel engine. The effect of this is to simultaneously improve the efficiency of the system while reducing the fuel consumption. Their aim was also to move away from chemical battery storage and thus they evaluated different modifications to diesel engines when CAES systems are introduced into the hybrid system.

This proposed Hybrid wind-diesel-CAES system directly supports the research question of this paper, and furthermore gives a strong indication of the renewed interest in compressed air technology. The solution proposed by the authors definitely holds a lot of value to existing diesel hybrid systems. The proposal is to use excess energy from wind-diesel system to store compressed air, which will then be used to assist the turbo-charger of the diesel via a directly coupled air turbine during low and fluctuating loads when there is not enough exhaust gas for the turbo charger to assist the engine. The compressed air can also be used to run a diesel engine quickly up to running speed. The paper claims that adding the CAES system to the existing hybrid can increase the diesel engine power by a factor of 5. [Hussein Ibrahim *et al*, 2007].

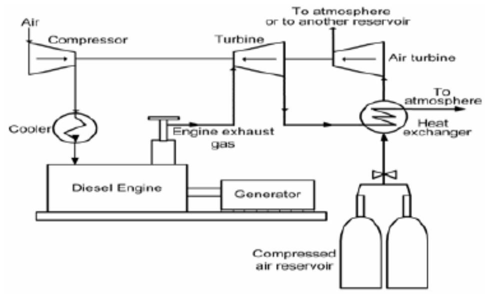


Figure 7: Illustration of the WDSAC with the Compressed Air Storage (CAS) turbine connected to turbocharger shaft (Hussein Ibrahim *et al*, 2007)

New Technology and Possible Advances in Energy Storage. Writen by John Baker. Ea Technology Ltd. Elsevier. 4 November 2008. Accessed: 20 June 2009. Webapge: http://ideas.repec.org/a/eee/enepol/v36y2008i12p4368-4373.html

This paper covers existing and possible future advances on energy storage systems. The following technologies are covered in the paper:

- Electrochemical Systems (batteries and flow cells).
- Kinetic Energy Systems (flywheels).
- Potential Energy Systems (pump storage and CAES).

The paper focuses mostly on advances made in the field of electrochemical storage systems with very little on the Potential Energy Systems, although he predicts a medium to high probability that there will be an increased uptake of these technologies in the market. The author indicates that development in the core storage technologies will be facilitated by advances in materials science, engineering, processing and fabrication. The paper also postulates that future energy storage technologies will be expected to offer improved energy and power densities, but predicts that in practice gains in longevity, cycle expectancy and cost may be more significant. The paper only looked at the large scale applications of Potential Energy Systems, and did not consider smaller applications which are definitely receiving increased attention from many researchers and developers. His prediction that the practicalities of energy storage systems can be seen as very valid with regards to HCEAS for small scale applications, when considering that compressed air systems have no cycle limitations and have the same lifetime expectancy as that of the application or energy system itself [John Baker, 2009].

Thermodynamic Analysis of Compressed Air Vehicle Propulsion. Written by Ulf Bossel. European Fuel Cell Forum. Accessed: 19 June 2009. Webpage: www.efcf.com/reports/E14.pdf

In his research paper Bossel evaluated claims made by the developers of air cars such as MDI and the subsequent questions regarding the performance of these vehicles by car manufacturers and automobile experts. The approach used was to calculate the actual efficiency and design that will be required for such a car to be effective. The theoretical analysis of the compression and later utilisation of the air showed that both sides are partially correct. The calculations in the paper showed that filling a 300 l tank with air at 20 °C and 300 bar would result in the storage of 51 MJ of energy. Under ideal reversible isothermal conditions this energy can be completely converted to mechanical work. However, under isentropic conditions not more than 25 MJ can be used for work, which yields an efficiency of 50%. The paper shows that through multistage compression with inter cooling between stages and using multistage decompression with inter-stage heating the expansion process can be brought closer to the isothermal ideal of close to 85% efficiency. The work of Bossel provides an excellent foundation for further research and this work could serve as the basis for HCAES system design principles for future investigation [Ulf Bossel, 2009].

Four-stage expansion	iso-thermal	isen-tropic	poly-tropic	poly-tropic	poly-tropic	poly-tropic	Units
Polytropic efficiency η_{exp}	∞	1.0	0.95	0.90	0.85	0.80	-
Polytropic coefficient n	1.0	1.4	1.37	1.35	1.32	1.30	-
Expansion work Wt_{34}	51	42	43	43	43	44	MJ
Energy in tank Wt_{13}	51	51	51	51	51	51	MJ
Efficiency W_{t34}/W_{113}	1.00	0.82	0.83	0.84	0.85	0.85	-
	100	82	83	84	85	85	%
Final temperature T_4	20	-78	-74	-70	-66	-62	°C

Table 1: Four-stage Expansion Results from Bossels's calculations [Ulf Bossel, 2009].

2.3: Compressed Air Literature

Compressed Air Power Secrets: Power Pneumatics for Inventors. Written by Scott Robertson. 3de edition. 2009. Accessed: 12 May 2009. Webpage: http://www.aircaraccess.com/pdf/caps%200-8.pdf

This book covers most of the theory and practical design aspects of designing an air vehicle. Chapters include the following topics:

- Compressing air.
- Using compressed air in engines and air motors.
- Compressed air and storage mathematics.
- New ways to compress air.
- Practical use of compressed air calculations.

The book contains a compilation of information on pneumatics and its application in designing a vehicle that can run on compressed air. This theory supports the work of this dissertation to develop a compressed air storage system, as this forms an inherent part of such a vehicle [Scott Robertson, 2009].

CHAPTER 3

METHODS AND DATA

3.1: Introduction

In order to evaluate the HCAES technology and compare it to existing energy storage technologies, it was important to first look at what is required from an ideal energy storage system and then to do an evaluation on the presently existing technologies. Important evaluation criteria are the cost of these technologies and their limitations. This analysis can then be used to formulate a possible HCAES design that could be locally built and would be reasonably priced and overcome the shortcomings of the presently available systems.

Equipment specifications for the components of the proposed HCAES design were then used to develop a theoretical model of the system. This model was then tested against the stand-by power requirements of the selected communications repeater station, which is presently supplied from a battery based system. This equipment data includes information on technologies such as air motors, alternators, converters and short-term battery storage.

3.2: Analysis of Installed Energy Storage Technologies

In order to analyse the ultimate energy storage device it is important to first identify the ideal characteristics of such a storage system. In this research work the focus was on addressing the energy storage requirements for small to medium scale renewable energy systems. Desired characteristics of such an energy storage system could be a combination of the following:

- High energy to weight ratio.
- High battery capacity.
- Quick recharge capacity.
- Long cycle life.
- Low cost.
- Robustness.

- Simple to maintain.
- Fast response.
- Current fluctuation tolerance.
- Low self discharge rate.
- Low effect of temperature.
- High cell or battery voltage.
- High turn-around efficiency.
- High depth of discharge.
- Low environmental impact.
- High safety factor.

It is important to identify the specific functional requirements that apply to a small or medium sized energy storage system. Functional requirements can be grouped into three main categories:

- Power Quality – provide energy for a second or less to ensure continuity of supply in response to system transients.
- Bridging Power – provide energy for seconds to a few minutes to ensure supply continuity while switching from one power source to another.
- Energy Management – in this application energy generation and consumption are de-coupled. Energy is stored when excess energy is available or cheap and used when energy is not available or expensive.

(Ref: http://electricitystorage.org/tech/technologies_comparisons_ratings.htm)

In the case of small to medium scale energy storage applications for renewable or back-up systems, at least two of the above functionalities will be required. The power quality or bridging component will depend on the type of energy storage technology and the required response time. Then the main energy management component, which will supply the load when energy supply is not available or disconnected, will always be required.

For the purposes of this document, the range of energy storage devices falling into the category "small to medium sized" is assumed to range from 1 kW to approximately 1 000 kW. The figure below indicates the performance of a number of commercially installed storage applications with respect to their time of discharge and rated power.

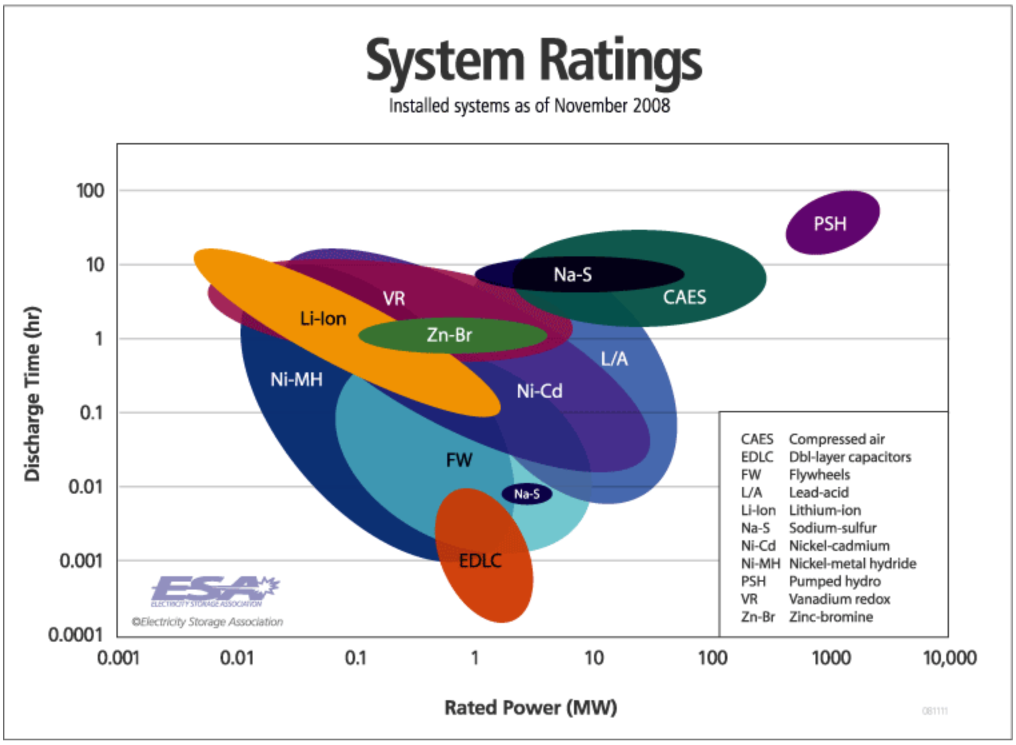


Figure 8: Energy Storage System Rating Comparison (source: http://electricitystorage.org/tech/technologies_comparisons_ratings.htm).

Based on the information in Figure 8 the most obvious technologies for small scale applications (less than 100 kW), which best satisfy the requirements of supply quality or bridging power are the following [Electricity Storage Association, 2003]:

- Nickel-metal hydride battery.
- Lithium-ion battery.
- Vanadium redox battery.

However, the above analysis is only based on time of discharge and rated power which does not take all the other desired characteristics of storage technologies into consideration. Using the technology comparison graphs from the electricitystorage.org website and found in appendix A to D, the comparison table below was developed to indicate the advantages and disadvantages of each available storage technology [Electricity Storage Association, 2003].

Technology Comparison						
Technology	**Capital Cost per Unit Power -$/kW**	**kWh/m³**	**kWh/ton**	**Cycles @ 80% DoD**	**Efficiency w/o power electronics - %**	**Per Cycle Cost - $/kWh**
Compressed Air (CAES)	80	n/a	n/a	12 000	75 (storage only)	0.05
Dbl-layer capacitors (EDLC)	200	20	15	50 000	98	0.08
Flywheels (FW)	6 000	15	12	30 000	95	0.1
Lead-acid (L/A)	600	50	28	800	75	0.7
Lithium-ion (Li-ion)	1 500	300	120	6 000	97	0.7
Sodium-sulphur (Na-S)	800	200	120	3 000	88	0.2
Nickel-cadmium (Ni-Cd)	1 000	60	40	2 000	65	0.7
Nickel Metal Hydride (Ni-MH)	50	310	300	100	40	n/a
Pumped Hydro (PSH)	900	n/a	n/a	30 000	80	0.01
Vanadium redox (VR)	700	25	25	3 000	80	0.15
Zinc-bromine (Zn-Br)	700	25	25	3 000	80	0.1

Table 2: Technology Comparison

From the comparison of storage technologies in table 2 the benchmark was taken as the Lead Acid battery technology, as this is the technology most frequently used in the study area for energy storage. This was then compared to the existing TACAS system.

Taking the above mentioned factors into consideration, the benchmark that will be used for comparison with the HCAES system in this research is shown in Table 3.

Cost/kWh - output	kWh/m³	kWh/ton	Cycles@ 80% DoD	Efficiency w/o power electronics - %	Per cycle cost - $/kWh
600	50	28	800	75	0.7

Table 3: Baseline for HCAES Comparison

3.3: Hybrid Compressed Air Energy Storage

Air is an abundant and clean resource with specific gas characteristics, which allow it to be compressed and expanded without any effect apart from the exchange of heat with the immediate environment. Thus, it can be used as a simple and effective way of storing energy for later use.

Compressed air technology is not new and has been used effectively in commercial applications since the beginning of the last century to drive mining machinery, locomotives, trams and even clocks. The technological advance of compressed air technology stagnated as electricity became the energy carrier of choice for most industrial applications. Compressed air has had certain niche applications in industrial and mining environments as it reduces explosion hazards and offers a certain amount of stored energy to ensure that production is not severely influenced by electrical interruptions. Some of the main advantages of compressed air are [Wikipedia, 2009, (12)]:

- Can be stored for extended periods.
- It is non-polluting.
- It is non-flammable.

- It is non-toxic.
- Most compressed air equipment is recyclable.
- Compressed air systems have a high cyclic life time.
- Air motors are simple, robust and deliver a high torque.

As with chemical batteries and hydrogen storage, the main disatvantage of compressed air is the indirect use of energy. Energy is required to first compress the air, after which decompressing the air releases the energy to drive air equipment such as air motors. The conversion between different energy carriers will result in losses, which will reduce the overall efficiency of such a system. Additional disadvantages are [Wikipedia, 2009, (12)]:

- When air is compressed it heats up, and heat energy is lost to surroundings.
- When compressed air is decompressed it cools down, reducing its working pressure.
- Moisture and particles in the air could effect or damage the equipment due to the high working pressures required.
- Not all the compressed air in the storage device can be utilised to do work.

Air can be compressed and stored using three different processes [Wikipedia, 2009 (13)]:

1. The first option is to perform the compression and storage of the air adiabatically, which implies that the heat that is generated during compression is also stored and then added back during decompression. Theoretically, an adiabatic process can be 100% efficient, but in practice cycle efficiencies close to 70% can be expected.

2. The second option is a diabatic process, where intercoollers between compression stages are used to dissapate heat to the atmosphere. Then, during decompression, the air is reheated by either adding fuel and igniting the air or by using heated metal mass. The highest efficiency achieved by a commercial installation is 54%.

3. The final option is to employ an isothermal process for compressing and expanding air. Once again efficiencies close to 100% can theoretically be achieved. In the isothermal process very effective heat exchangers are needed due to the fact that a constant heat exchange with the environment is required during compression and expansion. Currently this process is only used for low power applications as slow cycling is required to maximise heat exchange.

During research for this study, the only two commercial systems for small to medium scale energy storage applications that could be found, were the TACAS uninterrupted power supply system and the MDI stand-by generator. After initiating contact in an attempt to establish the cost and performance of both, only Active Power responded with the price of $110 000 US for their 85 kW/15min system.

	Energy Storage Technology			
	Lead-Acid Batteries	Flywheels	Compressed Air	Thermal Storage
Power Density	Good	Very Good	Fair	Excellent
Energy Density	Very Good	Fair	Good	Excellent
Cycle Life	Fair	Excellent	Very Good	Very Good
Footprint	Good	Excellent	Fair	Excellent
Runtimes	Very Good	Fair	Good	Very Good
Recharge Time	Good	Excellent	Fair	Very Good
Dynamic Response	Very Good	Excellent	Poor	Poor
Maintenance Cost	Fair	Very Good	Good	Very Good
Ambient Temp	20-25°C	0-40°C	0-40°C	0-40°C
Life in UPS app.	3-12 years*	20 years	20 years	20 years
Environmental	Toxic	Benign	Benign	Benign
Installed Cost	1.0-1.4	1.4	5.0	5.0

* 3-5 years for VRLA, 8-12 years for flooded jars.

Table 4: Energy Storage Technologies Compared [J.R Sears, 18].

The TACAS system incorporates three different technologies in order to offer an environmentally friendly uninterrupted power supply. It combines air storage with thermal storage and a flywheel in order to firstly improve the efficiency of the air decompression during power delivery and, secondly, to ensure quality of supply or bridging power. The air storage tanks operate at 31 MPa or 310 bar pressure and are based on the self-contained breathing apparatus (SCBA) tanks used by divers and fire fighters. The thermal storage unit consists of a stainless steel core with internal passages to transfer heat to the air being decompressed, which is kept at 977 K by normal electric resistance heaters. The flywheel is a new design that will supply the full back-up load for three seconds (85 kJ x 3s = 255 kJ, if taking 85 kW for 15 minutes) [J.R Sears, 18].

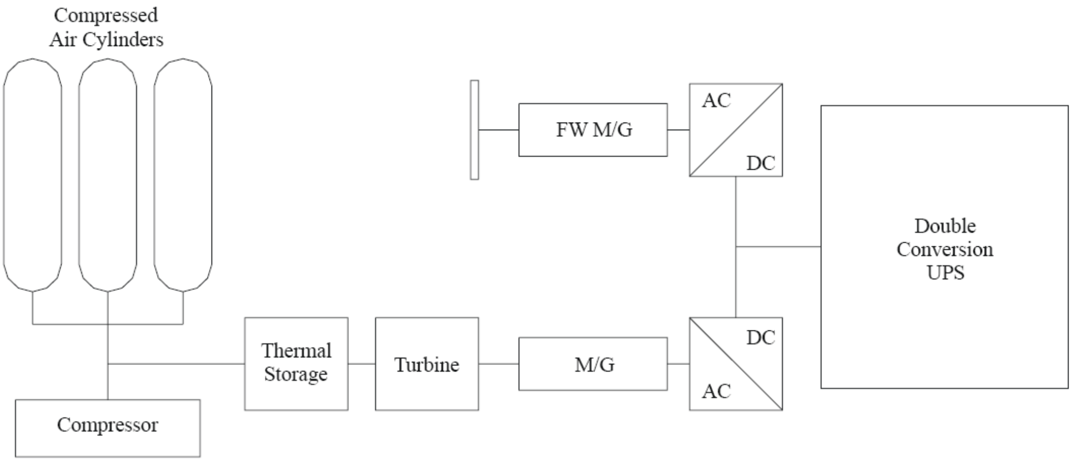


Figure 9: Thermal and Compressed-Air Storage (TACAS) Diagram [J.R Sears, p3, 18].

The paper by John Sears indicated an exit air flow of 700 cubic feet of free air or 21 m^3 from the expansion turbine used in the TACAS system for an output supplying a load of 84 kW for 15 minutes. The turbine therefore supplied 76 MJ of energy or 21 kW of power to the load in those 15 minutes [J.R Sears, 18]. Compared to this, the Ingersoll Rand air motor, KK6M is an 18.64 kW motor which requires 19 m^3 of air per minute, and would have supplied only 16.776 MJ in 15 minutes [Ingersoll Rand, p71, 19]. Based on this analysis the TACAS system can produce 4 times more power than the commercial KK6M air motor with only an additional 2 m^3 of air per minute, not taking into account the compressor, air storage and thermal storage losses. If these losses are taken into consideration it must be assumed that the overall system efficiency would be much less than the 40.7 % estimated by Bossel for this type of system, as just the energy lost to keep the thermal system at 977 °K would significantly increase per cycle cost and at the same time bring efficiency down by a large margin.

The air storage requirement for the TACAS system is 21 m^3 x 15 = 315 m^3. Assuming that the air is stored at 310 bar pressure the tank size will be (315 m^3 x 101.3 kPa) / 31 000 kPa = 1.029 m^3, with a weight of 361 kg if the weight of free air is taken as 1.205 kg/m^3 at 20 °C.

	Cost/kWh - output	kWh/m³	kWh/ton	Cycles @ 80% DoD	Efficiency w/o power electronics - %	Per Cycle Cost - $/kWh
Baseline	600	50	28	800	75	0.7
TACAS	1294	47	58	12000	40.27 [9]	n/a

Table 3: Baseline vs TACAS Comparison

From the TACAS white paper [J.R Sears, 18] there was no mention of what the actual efficiency for the system was, and here the estimate from the paper by Bossel in his analysis was used for comparison purposes. Per cycle cost could not be derived from the information of the TACAS system as there was little or no information on the cost of keeping the thermal energy unit at the required temperature or what the losses will be to keep the flywheel at rated stand-by speed.

3.4: Brakfontein Repeater Station

The Brakfontein Repeater Station is used to relay radio and microwave signals for voice and signal communication purposes. Some of the communication is also used for monitoring electrical substations and to send supervisory control signals to switch equipment within the substations or on the electrical lines. This repeater station is normally supplied by an 11 kV distribution line and the design standards specify stand-by power for 12 hours.

The site documentation indicates an installed back-up system with main and a back-up battery bank, each with 24 Chloride, FHP59, 2 V cells, as indicated in the table in appendix G.

According to the manufacturer, current discharge specifications for these cells, as indicated in appendix H, give the rated discharge for 1 hour of 1 297 A and the C10 rating of 3 800 A/h at 25 °C. Therefore, it can be extrapolated that discharge for 12 hours will be 300 A, with a battery voltage of 48 V, which will give a total storage capacity of 300 x 48 x 12 = 172 kWh.

3.5: Selected HCAES Equipment for Design

Following the literature and internet research and subsequent to the evaluation of the existing material on HCAES systems, the various alternatives were investigated to find all the available equipment that could be used in an off the shelf design. Based on the TACAS research, the air storage pressure needed to be at least 30 MPa or more, with an air motor that can supply an alternator of at least 15 kW, after losses, in order to supply the stand-by load of the repeater station. The air storage for 12 hours will depend on the efficiency and the free air usage of the air motor.

3.5.1: High Pressure Compressor

The search for available compressors that can deliver the required pressure yielded several different units from two major manufacturers. Based on the requirement for a minimum pressure of 30 MPa, and considering the required volume of air to be compressed per minute, the following Ingersoll Rand T30 High Pressure compressors were considered, with specifications as given in table 4.

Figure 10: Ingersoll Rand T30 High Pressure Unit [Ingersoll Rand, p10, (20)].

Specifications

Model	Bare Unit	Motor kW	Motor hp	Pressure Max bar g	Receiver Litres	Piston Displacement l/min	Revolutions per minute rpm	Dimensions L x W x H cm	Weight kg
High Pressure									
231X30	231	2.2	3.0	35	N/A	211	670	87 x 51 x 51	100
7T2X100	7T2	8.5	12.5	35	N/A	1050	820	124 x 67 x 84	275
15T2X200-35	15T2	15	20	35	N/A	1471	950	143 x 84 x 87	415
15T2X200-70	15T2	15	20	70	N/A	1230	790	143 x 84 x 87	415
15T4X200	15T4	15	20	241	N/A	988	930	150 x 78 x 108	505
H15T4X200	H15T4	15	20	345	N/A	988	930	150 x 78 x 108	525

Table 4: Ingersoll Rand T30 High Pressure Unit Specifications [Ingersoll Rand, p10, (20)].

Figure 11: Bauer High Pressure Horizontal Compressor [Bauer, p10 (21)].

	Model	Motor		Available Series			Capacity 15 scfm 30 45 60 75 90 105 120 135 150 165
		hp	kw	A	G	C	425 l/min 850 1275 1700 2120 2550 2970 3400 3820 4245 4670
	Compressors						
1000 psig (69 bar)	12.4	5	3.5	•			
	22.5	15-20	11-15	•			
	23.4	30-40	22-30	•			
	25.4	50	37	•			
	28.2	60-75	45-55	•			
	25.5 1)	100	75	•			
	28.3 1)	125-150	90-110	•			
5000 psig (345 bar)	100	5	3.5	•	•	•	
	120	7.5	5.5	•	•	•	
	15.1	7.5-15	5.5-11	•	•	•	
	150	15	11	•			
	180	20	15	•			
	15.2	20	15			•	
	220	25-30	18-22	•	•	•	
	23.1	40	30		•	•	
	230	40	30	•			
	250	50-60	37-45	•		•	
	280	75-100	55-75	•		•	

Table 5: Bauer High Pressure Compressors Specifications [Bauer, p10 (21)].

3.5.2: Alternator

Based on the calculated requirement of 14.4 kW of stand-by power required by the repeater station, the most likely locall alternator found was the Sincro SK 160 LA1, single phase, 4 pole alternator. This alternator can deliver 20 kVA at 1 500 rpm at a power factor of 0.8 and requires a 22 kW prime mover.

Figure 12: Sincro SK 160 LA1, 20 kVA Alternator [Sincro (22)]

3.5.3: Air Motor

Following on from the alternator selection an air motor that can deliver at least 22 kW is required in order to ensure the full output of 16 kW can be delivered to the load. The first motor considered was the KK6M, but it can only supply a maximum output of 18.64 kW, and thus the larger KK5B550 motor was selected as it can deliver the required 22.3 kW.

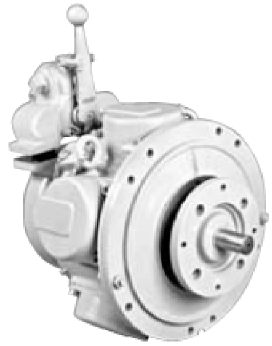


Figure 13: Ingersoll Rand KK5B Piston Air Motor [Ingersoll Rand, Air Motors, p81 (19)].

Model	Max. Power		Speed at Max. Power	Free Speed▲	Starting Torque		Stall Torque		Air Consumption at Max. Power		Weight	
	hp	kw	rpm	rpm	lb.-ft.	Nm	lb.-ft.	Nm	scfm	m^3/m	lb.	kg
Reversible												
KK5B546	29	21.6	900	1800	183	248	300	407	795	22.5	—	—
KK5B550	30	22.3	880	1750	202	274	325	441	850	24.1	—	—

Table 6: Ingersoll Rand KK5B Specifications [Ingersoll Rand, Air Motors, p81 (19)].

3.5.4: Air Storage

All the analysis in this dissertation has been based on the fact that a minimum air pressure of 30 MPa will be required, various storage receivers or tanks have been found on the Bauer Group’s website which could be used effectively to store the required amount of air. The two types of receivers that can be used are the ASME or Dot receivers. Their working pressures and sizes are given in table below.

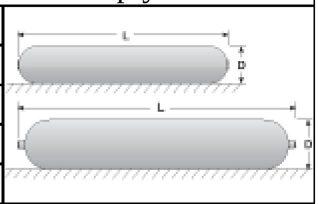
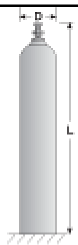
Working Pressure PSIG	Water Volume SCF	Water Volume Gallons	Capacity @ max. Pressure SCF	Dimensions Ø - Length INCH	Weight LBS	
All values are approximate and subject to change. Weight is for empty receiver.						
ASME Receivers						
5000	1.47	11	436	9 9/16 - 54	400	
6000	1.47	11	491	9 9/16 - 54	400	
7000	1.47	11	537	9 9/16 - 54	400	
Dimensions are for bare receiver only.						
DOT Receivers						
4500	1.59	11.9	444	9 5/16 - 55	145	
5000	1.59	11.9	472	9 3/8 - 56	160	
6000	1.53	11.4	509	9 9/32 - 55	190	
Dimension includes shutoff valve.						

Table 7: Bauer Air Storage or Receiver Tanks [Bauer Group (23)]

3.5.5: Bridging Power

As previously mentioned, one of the requirements of the final system is some type of bridging power or power quality component that would be able to supply full load when the main supply fails in order to give sufficient time for the compressed air system to come online. This can be achieved by a combination of different technologies, as with the TACAS system. The available options included super capacitors, a fly wheel or a battery and inverter system with a fast response able to supply enough power to the load for the time it takes the air motor to run up and supply the required energy. For the purpose of this paper the focus is on the ability of the air system to supply the load for 12 hours, thus no selection or options for power quality or bridging power were considered.

3.5.6: Inverter and Control System

Commercially available products, such as the outback back-up system, are available for the inverter and control systems. The only required modification would be changing the programming of the control circuit for the standard diesel generator to accommodate the air control system.

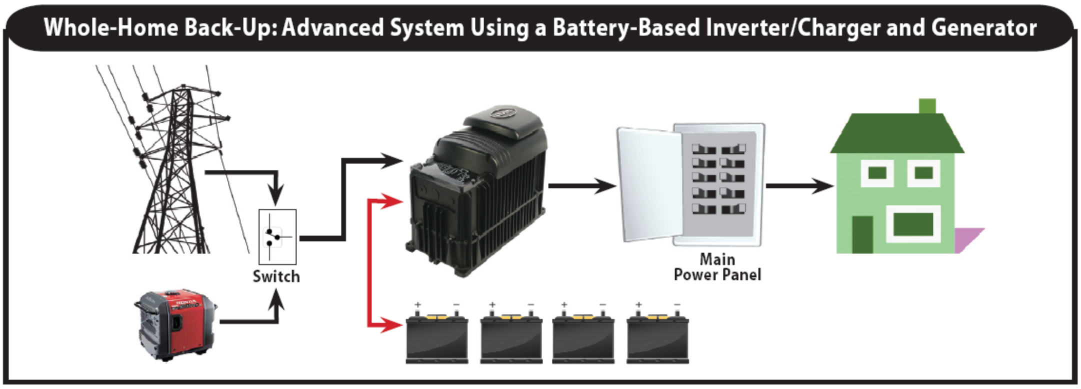


Figure 14: Outback Advanced System Using a Battery-Based Inverter/Charger and Generator [Outback Power Systems (25)].

The VFX3048E outback inverter has an output of 3 kW at 230 VAC and frequency of 50 Hz. In order to increase the power delivery the Outback units can be stacked or paralleled up to 36 kW. To supply the standby load of 14.4 kW, five units can be stacked together, giving a total capacity of 15 kW. Again, the efficiency of the power conversion was not taken into consideration as the focus of research was on the compressed air system.

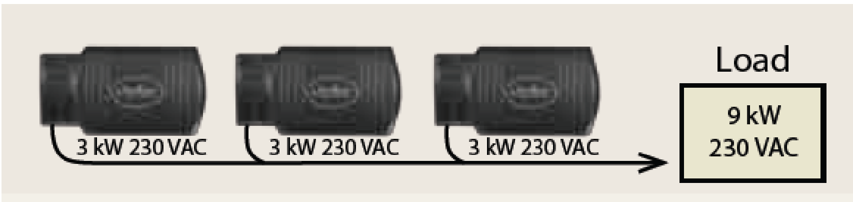


Figure 15: Parallel Stacking of Outback Units [Outback Power Systems , Product Guide (26)].

3.6: Selected HCAES Equipment for Design

From the above equipment selection a very simple off the shelf design as indicated in figure 16 below was used as the basis of a local HCAES design. The focus of the analysis will be on the energy management function, the storing of energy for use to supply the load if the main supply should fail.

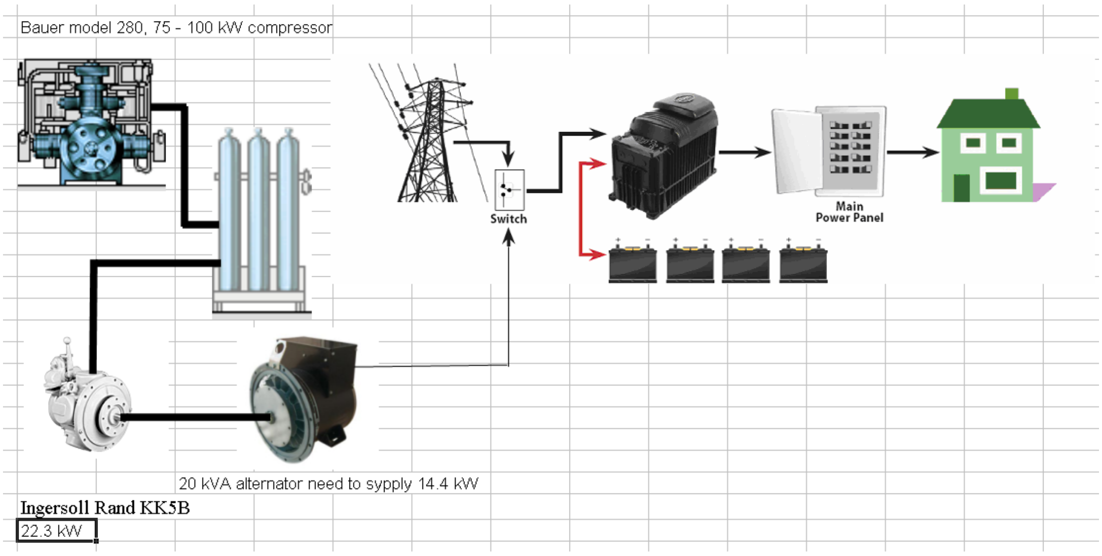


Figure 16: Proposed design for an off the shelf HCAES system

3.7: Methods and techniques

Taking the development of the TACAS system as a model to work from, information was sourced on available air equipment currently used by industry to develop an off the shelf system for storing energy.

Basic "back of the envelope" calculations were performed to get an idea of the ability of the system and to estimate approximate efficiencies. Boyle's law is used as the basis for an Excel spread sheet to calculate the power and air production of the selected compressor, after which the air requirements were calculated from the consumption of the air motor. In order to verify the results of the calculations, the formulas used by Bossel in his paper [Ulf Bossel (9)] were then used. The results from the analysis follow in the next chapter.

The analysis was done by firstly calculating the amount of air that would be required to drive the selected KK5B550 air motor for one hour. This was then compared with the amount of compressed air from the Igersoll Rand T30 high pressure compressor per hour, whose delivery was found to be insufficient to supply the required air to drive the air motor for the time required. A larger compressor was then selected, the Bauer 280, which could deliver close to 3.5 m^3/min. Even with the higher air delivery it was not enough to run the air motor for the expected time, after which the efficiency of the air motor was scrutinised by comparing the energy in and the energy out. The analysis of the motor efficiency gave a strong indication that the motor was not designed for efficiency, but more for performance.

CHAPTER 4

RESULTS FROM ANALYSIS OF PROPOSED DESIGN

4.1: Introduction

A spreadsheet was used to first calculate the amount of air that can be stored by the Bauer, model 280, 75 - 100 kW compressor and then this was compared to the air supply requirements of the Ingersoll Rand KK5B550, 22.3 kW air motor in order to deliver the required power to the Syncro 16 kW alternator. Boyle's law was used to calculate the air delivery of the compressor, and reverse calculations were used to derive the air storage requirements of the air motor. The results of these calculations were found to be completely unacceptable when taking the 75% efficiency from the derived base case into consideration. In order to test the results, the quantity of stored energy within the compressed air and the amount of air used by the motor were compared. The result of this comparison gave a very strong indication of the efficiency of such a off the shelf compressed air system, not taking into account the losses of the components that would need to supply the bridging power or power electronics.

4.2: Results from Boyle Calculations

From Boyle's Law:

P1 x V1 = P2 xV2

Compressor Air Production Per Hour					
V0	204	m³/h	V1	0.599	m³/h
P0	101.3	kPa	P1	34 500	kPa

Table 8: Bauer, model 280, 75 - 100 kW Compressor Air Production.

Motor Air usage from tank pressure						Motor free air usage per hour		
V3	3.488	m³/h	V4	194.1039	m³/h	V5	1 188	m³/h
P3	34 500	kPa	P4	620	kPa	P5	101.3	kPa

Table 9: Ingersoll Rand KK5B550, 22.3 kW air motor usage.

In calculating the air motor air usage it was assumed that the outlet air will be at ambient pressure of 101.3 kPa. The large discrepancy between the air delivered to the air receiver by the compressor driven by a 100 kW motor, and the air required by the air motor to deliver 22.3 kW of power showed such a large discrepancy that a additional method was needed to calculate the amount of energy stored by the compressor an hour, and the amount of stored energy actually consumed by the motor in an hour.

4.3: Stored Air Energy Calculations

According to the paper by Bossel [Ulf Bossel (9)] the energy contained by the compressed air can be calculated using the following formula:

W = P1 x V1 x ln (P3/P1) KJ

Energy Stored Per Hour			
E = V0 x P0 x ln(P1/ P0)			
	E1=	120491.100	kJ
	P=kJ/(1000*3.6)	33.470	kW
Compressor Electricity Consumption per hour			
Comp kW=	100 kW		

Table 10: Bauer, model 280, 75 - 100 kW Compressor Air Energy Stored per hour.

Energy Used Per Hour Motor		
E = V4 x P4 x ln(P3/P4)		
E1=	483663.557	kJ
P=kJ/(1000*3.6)=	134.351	kW

Table 11: Ingersoll Rand KK5B550, 22.3 kW compressed air energy used by air motor.

From the result from the calculations it was shown that the compressor actually stored 120 MJ of power from an assumed input of 100 kW, and the motor required 483 MJ to deliver 22.3 kW.

4.4: Compressed Air System Efficiency Calculations

Comp Calculated Efficiency using per hour kW		
ηcomp=Compressor Energy Stored/Energy Compressor in x 100%		
ηcomp=	33.470	%
Motor Calculated efficiency		
ηmot=Energy Air Motor out/Energy Air Motor in x 100%		
ηmot=	11.287	%
Final efficiency for compressed System		
ηT=	ηcomp x ηmT	%
ηT=	33.470 x 11.287	%
ηT=	3.78	%

Table 11: Compressed Air System Calculated Efficiency

4.5: Discussion of results

The initial basis of this research was the assumption that compressed air could offer an alternative to commercial energy storage technologies. The focus was on off the shelf products that could be combined in order to deliver the required energy storage and delivery method. The information from suppliers indicated that the overall efficiency of the complete system would be very low. During the first calculations the unsatisfactory results indicated that there may possibly have been wrong air flow calculations used. The actual air flow given in the specifications of the compressors and air motors was confirmed to be free output air flow rate of standard intake condition from the Atlas Copco Compressed Air Manual [27, p13] and these are given in litre per second (l/s) or litre a minute (l/min).

The initial analysis was based on the Ingersoll Rand T30 high pressure compressor and the Bauer series of compressors. However, more detailed analysis indicated that the T30 could only supply 0.988 m^3/min, which did not come close to the required volume of air to drive the air motor. Therefore the larger Bauer, model 280 specifications were used, which can supply 3.4 m^3/min. Even after increasing the compressor size there was a large discrepancy between compressor air delivery and air motor input required to give the torque required to drive the alternator. The results of both historical and recent research indicate that the main theme is that in order to increase the power delivery, the air needs to be reheated as it is decompressed. When this is done in stages it significantly increases the efficiency of the system. In the analysis presented here no reheating was considered as the actual performance of the unmodified, commercially available, air equipment needed to be evaluated.

Due to very low efficiencies and unavailability of data of air equipment cost, it was not possible to effectively compare the off the shelf HCAES system to the benchmark Lead Acid battery system. Yet if taking into consideration that the compressor will compress 204 m³ of air to 0.59 m³ an hour and it will contain roughly 33 kW of power, 0.0178 m³ of compressed air will contain 1 kW of power. This 1 m³ of air compressed to 345 bar will contain 60 kW of power.

	Cost/kWh – output	**kWh/m³**	**kWh/ton**	**Cycles @ 80% DoD**	**Efficiency w/o power electronics - %**	**Per Cycle Cost - $/kWh**
Baseline	600	50	28	800	75	0.7
Off the shelf	n/a	60	n/a	12000	3.8	n/a

Table 12: Comparison of off the shelf design with Lead Acid Benchmark.

From the above comparison it can be seen that although air could compare in certain conditions with Lead Acid energy storage, the very low efficiency will negate any possible advantages an off the shelf HCAES might have.

CHAPTER 5

DISCUSSION

5.1: Introduction

The work done during the research revolved around answering the main research question from available literature, i.e., if HCAES could offer a viable alternative solution to energy storage requirements of small to medium size renewable energy systems. Due to the nature of study, no laboratory work could be performed to test the answers found during the study or to prove the results from calculations. In spite of this there is a strong indication that the results for the proposed design may be correct, based on the information that can be found in the information given in the specification sheets of the Bauer, model 280 [Bauer Group (23)] compressor and the Ingersoll Rand KK5B550 [Ingersoll Rand (19)] air motor. This is based on the comparison of the free output air rate per minute.

5.2: Discussion

The air equipment that was considered in this dissertation is currently being utilised in industrial applications where the specific characteristics offer a benefit to various production processes. The equipment under consideration was never designed or intended to be used in a power storage and delivery system as would be required by a communication repeater station. The fact that the compressed air system is storing energy cannot be disputed, but there does not seem to have been any great motivation to increase equipment efficiencies due to the nature of the standard applications, where energy efficiencies are not important. This may change as energy becomes a scarce and expensive commodity.

The initial assumption was that increasing the pressure of the stored air, more air can be stored in smaller vessels, which of course is correct. However, this increases the losses considerably. This is due to the fact that as the pressure of air is increased and its volume is reduced heat is being produced that will be passed to atmosphere. This is a direct loss of energy which decreases the energy contained within the air that is being stored. In addition, the air entering the storage tank will be at temperatures ranging from 40 to 80 °C, depending on compressor cooling and will then cool down to ambient temperature over time, further decreasing the energy content of the stored air. This was not considered as the initial calculations gave a strong enough indication of the overall effectiveness and efficiency of the air system.

The process that is being used by the compressor is a diabatic process, involving cooling between stages to dissipate the heat to the atmosphere. The Bauer, model 280 compressor has a four stage inter-cooling system and the final temperature of air leaving the compressor could not be found from manufacturer specification sheets. Based on calculations, the efficiency of the compressor was calculated to be 33.47% to compress air to 345 bar pressure, delivering 204 m^3/h of free air. This is based on the assumption that the required input power would be 100 kW to drive the compressor.

The Ingersoll Rand KK5B550 air motor uses an isothermal process, exchanging constant heat with the environment during expansion of air through the motor. Theoretically, 100% efficiencies could be achieved when very effective heat exchangers are used and the air is expanded slowly in order to maximise heat transfer. However, the KK5B550 air motor does not seem to have effective heat exchange properties and this can be clearly seen based on the amount of air required in order to deliver 22.3 kW of power to the alternator. The amount of air from an efficient motor using the isothermal process that would deliver 22.3 kW can be calculated as:

Energy Required, Q = kW x 3.6 MJ
Energy Required, Q = 22.3 x 3.6 MJ
Energy Required, Q = 80.28 MJ

Air required to deliver 22.3 kW = V1

$$Q = P1 \times V1 \times \ln (P3/P1) \text{ kJ}$$

$$80280 = 101.3 \times V1 \times \ln (34500/101.3) \text{ kJ}$$

$V1 = 80280/(101.3 \times 5.83)$

$V1 = 135.9\ m^3$

The previous calculation clearly indicates that the 204 m^3/h of free air delivered by the compressor should be more than enough to drive an efficient air motor, yet the KK5B550 air motor requires 1 188 m^3/h of free air - almost eight times as much air as predicted by the ideal calculations. Based on the reported results of the TACAS system, which incorporates inter-heating, modifying the KK5B550 air motor with inter-heating could reduce the air consumption to 297 m^3/h. The calculated efficiency of the air system without modification was 3.7%. This means that the compressor is required to deliver 1 188 m^3/h, using an assumed 100 kW while needing to run for 5.7 hours to produce enough air to supply the air motor for one hour. The power consumption for the compressor would be 579 kW to supply the required air the air-motor will need to deliver 22.3 kW for one hour. The resultant overall efficiency of 3.7 % is not suitable for any form of energy storage application. The foregoing analysis does not even include the losses that would be associated with the power electronics or the bridging power component.

The low efficiencies as described above show why all the current research and new commercial applications are focussed on new, innovative and efficient designs and/or modification required for air motors, combined with other technologies such as super-capacitors, thermal heat storage and flywheels. Both the TACAS [4] and MDI literature mention this requirement in order to improve the efficiencies of a HCAES system. If a HCAES system using the identified off the shelf air equipment would have been used to supply the standby power for the selected application the input power required would have been 579 x 12 = 6 828 kW for a storage capacity of 172 kWh. Comparing this to the lead acid battery that is currently used with an efficiency of 75%, it is clear that a HCAES system using off the shelf equipment without modification and combining it with other technologies cannot be considered as an alternative solution to conventional chemical battery storage system.

CHAPTER 6

CONCLUSIONS

6.1: Conclusions

In this dissertation, it was shown that compressed air has been used for more than a century for applications ranging from drills to locomotives and power tools. Compressed air technology has been receiving renewed interest based on the twin imperatives of fossil fuel scarcity and the drive for renewable energy sources. This research evaluated HCAES technology in order to find out if it could offer a viable alternative energy storage solution for small to medium scale renewable energy systems.

Using the existing energy storage technologies as a baseline to compare new HCAES technology such as the TACAS system it was clearly shown with the available information that, besides a high life cycle and environmental advantages, the TACAS system does not seem to be an effective alternative to existing energy storage technologies. The off the shelf design without any modification to include inter-heating stages in the decompression stage and with a calculated efficiency of 3.8% will have very high per cycle cost and will not be a viable alternative to conventional battery storage.

It must be mentioned that with further research it would be possible to increase efficiencies of HCAES systems closer to the ideal. Research is improving compression and decompression using more effective isothermal processes, with much more efficient heat transfer materials, and adding intermediate air receivers between pressures which will increase the tank time helping more effective heat transfer to take place.

6.2: Recommendations

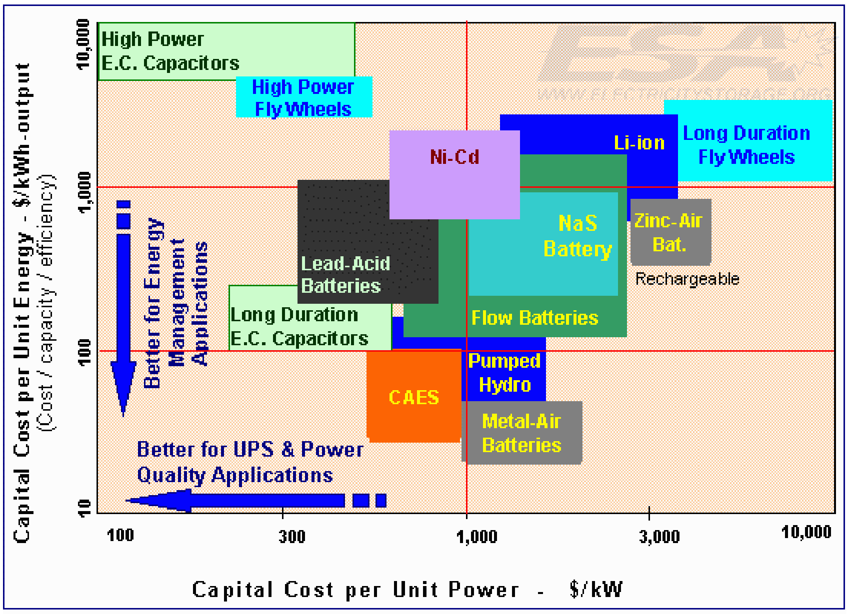
Initially, the information contained in this document was obtained from suppliers. However, the information provided did not completely match the information required to perform detailed analysis. It would also be advantageous to perform laboratory measurements to confirm the quoted results and to test the efficiency of the complete system.

Further research that could possibly help making the HCAES technology more viable and that could increase efficiencies of current air equipment include, but is not limited to the following:

- Efficiant heat exchangers for compression and expansion stage to facilitate easier exchange of heat with environment.
- Compressed air motors with inter-heating between stages.
- Split compressors with intermediate settling or heat exchange tank for higher pressures.
- Air-oil or air-water hybrid CAES system.
- Solar heating for heating thermal storage unit in expansion stage.
- Highly insulated thermal storage unit with low heat exchange properties.

APPENDICES

Appendix A: Capital Cost of Energy Storage Systems



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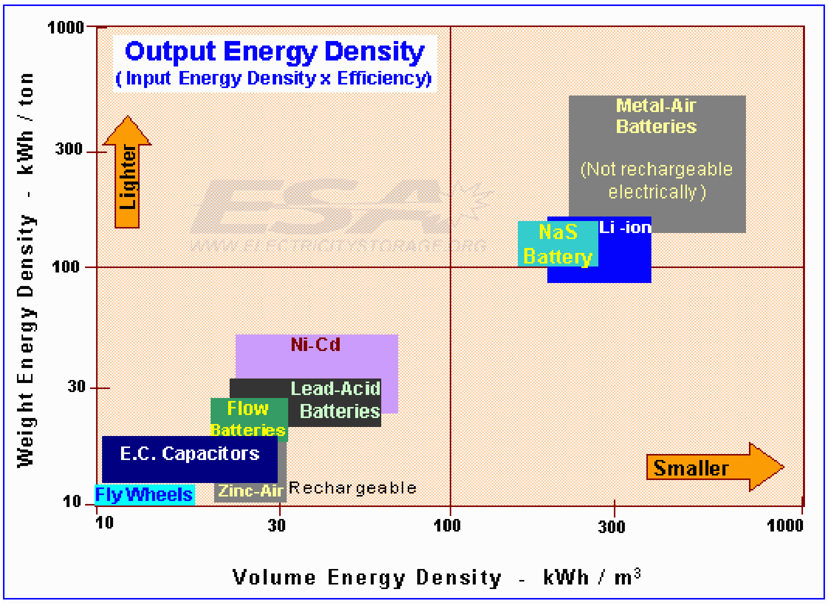
Appendix B: Size and Weight of Energy Storage Systems



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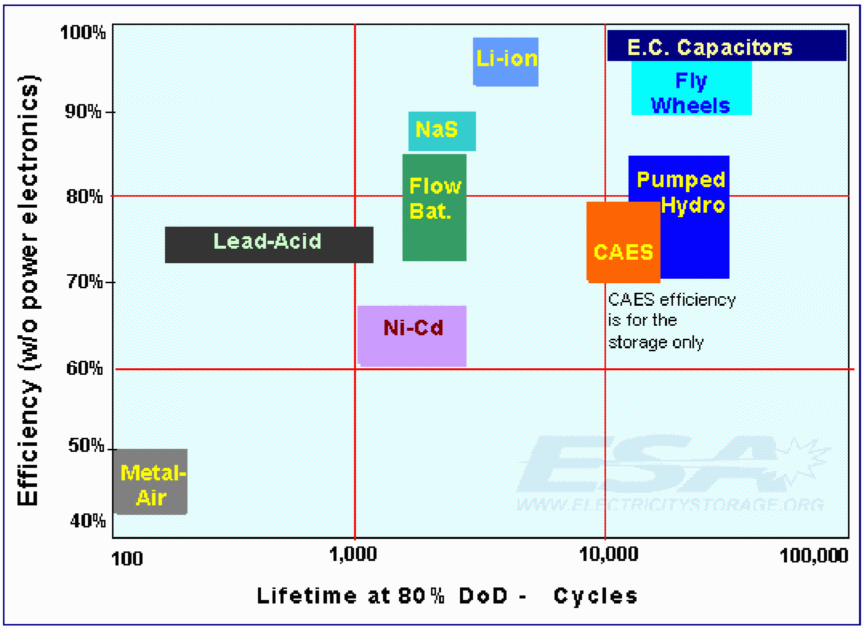
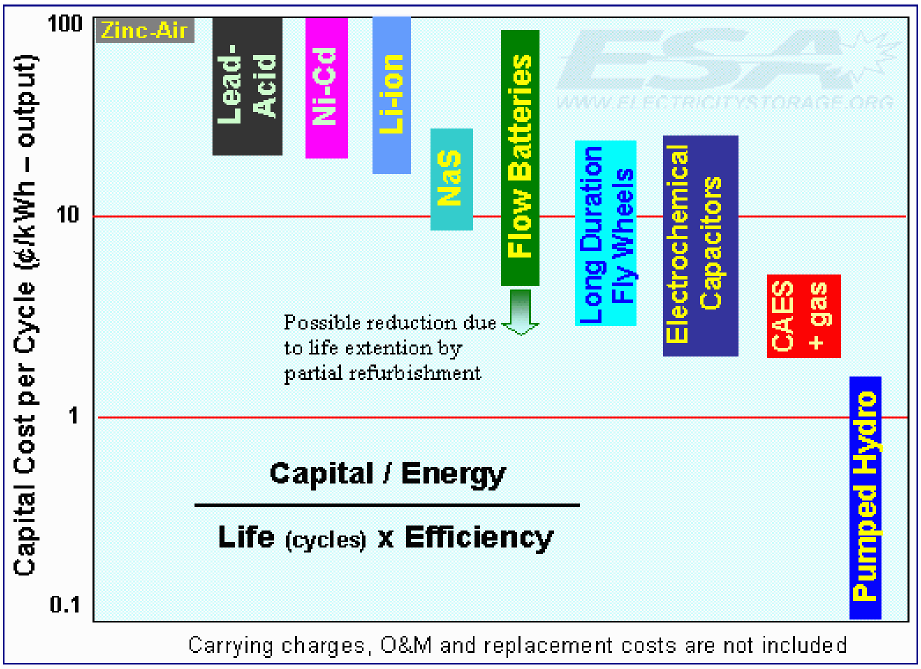
Appendix C: Life Efficiency of Energy Storage Systems



(source:

http://electricitystorage.org/tech/technologies_comparisons_lifeefficiency.htm).

Appendix D: Per Cycle Cost



(source:

http://electricitystorage.org/tech/technologies_comparisons_percyclecost.htm.)

Appendix E: Brakfontein Battery Banks and Chargers

Main 1

Station	**Brakfontein**		Battery Function		**Radio**
Battery Manufacturer	**Cloride**	Type	**FHP59 C10@25 °C 3800 A**	Cells	**24**
Charger	**Siemens CHR-B**	Float I		**233**	
	50 V/300A	Rapid I		**233**	
Float V	**54**	Boost I		**105**	
Boost V	**56.4**	Standing Load		**5.6 A**	
Equalize V	**62.4**				

Main 2

Station	**Brakfontein**		Battery Function		**Radio**
Battery Manufacturer	**Cloride**	Type	**FHP59 C10@25 °C 3800 A**	Cells	**24**
Charger	**Siemens CHR-C**	Float I		**233**	
	50 V/300A	Rapid I		**233**	
Float V	**54**	Boost I		**105**	
Boost V	**56.4**	Standing Load		**10.5 A**	
Equalize V	**62.4**				

Appendix F: FHP59 Cell Specification Data

Product Specification Data									
Type	Nom V	C10@ 25°C	L mm	W mm	H mm	Mass kg	Acid l	Cell Arrangement	Cell Centre
FHP 59	2	3800	509	368	682	234.1	59.4	E to E	394

Constant Current Discharge Data (amps at 25 °C)													
Cell / Bat Type	VpC	5 Min	10 Min	15 Min	20 Min	30 Min	45 Min	1 Hr	2 Hr	3 Hr	5 Hr	6 Hr	8 Hr	10 Hr
FHP 59	1.60	4693	4279	3865	3382	2899	2381	2036	1311	994	683	600	483	414
	1.65	4314	3951	3555	3158	2733	2278	1947	1277	978	680	597	480	412
	1.70	3882	3537	3209	2882	2537	2157	1844	1242	957	673	594	476	411
	1.75	3458	3130	2837	2578	2295	2002	1705	1191	936	665	583	469	404
	1.80	3027	2726	2457	2243	2036	1812	1558	1104	897	647	569	462	399
	1.85	2578	2298	2098	1908	1712	1512	1297	970	820	607	535	438	380

(source: http://www.battery.co.za/)

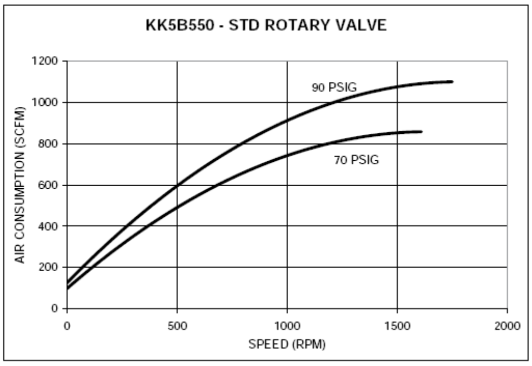
Appendix G: Common Properties of Air

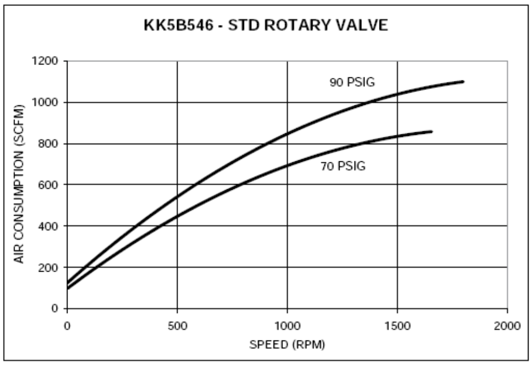
Temperature - *t* - (°C)	Density - *ρ* - (kg/m³)	Specific heat capacity - c_p - (kJ/kg K)	Thermal conductivity - *l* - (W/m K)	Kinematic viscosity - *ν* - (m²/s) x 10^{-6}	Expansion coefficient - *b* - (1/K) x 10^{-3}	Prandtl's number - P_r -
-150	2.793	1.026	0.0116	3.08	8.21	0.76
-100	1.980	1.009	0.0160	5.95	5.82	0.74
-50	1.534	1.005	0.0204	9.55	4.51	0.725

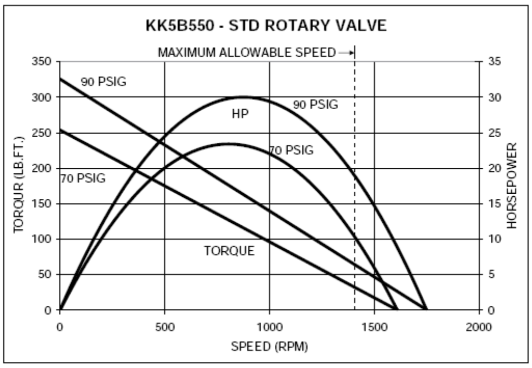
0	1.293	1.005	0.0243	13.30	3.67	0.715
20	1.205	1.005	0.0257	15.11	3.43	0.713
40	1.127	1.005	0.0271	16.97	3.20	0.711
60	1.067	1.009	0.0285	18.90	3.00	0.709
80	1.000	1.009	0.0299	20.94	2.83	0.708
100	0.946	1.009	0.0314	23.06	2.68	0.703
120	0.898	1.013	0.0328	25.23	2.55	0.70
140	0.854	1.013	0.0343	27.55	2.43	0.695
160	0.815	1.017	0.0358	29.85	2.32	0.69
180	0.779	1.022	0.0372	32.29	2.21	0.69
200	0.746	1.026	0.0386	34.63	2.11	0.685
250	0.675	1.034	0.0421	41.17	1.91	0.68
300	0.616	1.047	0.0454	47.85	1.75	0.68
350	0.566	1.055	0.0485	55.05	1.61	0.68
400	0.524	1.068	0.0515	62.53	1.49	0.68

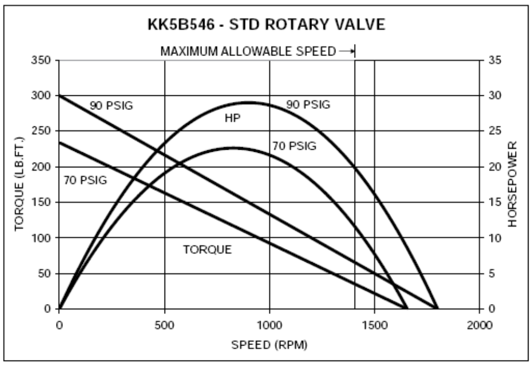
Reference: The Engineering Toolbox. Air Properties. 2005. Accessed: 12 June 2009. Webpage: http://www.engineeringtoolbox.com/air-properties-d_156.html

Appendix H: Performance Graphs for Ingersoll Rand KK5B Air Motor [Ingersoll Rand, Air Motors, p81 (19)].









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