University of Southern Queensland

Faculty of Health, Engineering & Sciences

Small Compressed Air Energy Storage Systems

A dissertation submitted by

Kayne Herriman

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Abstract

The storage of energy is emerging as a greener way to support our existing electricity networks and improve the stability of our grids, as we step forward into a cleaner future and becomes more dependent on intermittent renewable generation sources.

Australia is seen to be blessed with an abundant of renewable energy resources and it has been said that Australia is the Middle East of renewables. These “free” resources substantially exceed Australia’s total energy demand, both currently and into the foreseeable future.

Most energy storage systems require the useful energy to be converted from its initial state into another form, which is more suitable for storage. When ready to use, it’s then converted back into a useful form. With each conversion there are losses associated which affect efficiency, for this reason efficiencies of 100% are not achievable.

Compressed Air Energy Storage (CAES) is not an unproven technology and on a large scale there are two existing CAES plant in the world. The first plant ever built was in Huntorf Germany, which was commissioned in 1978 and capable of producing 321 MW for two hours. The second was in McIntosh Alabama USA, which was commissioned in 1991 and capable of producing 190 MW for 26 hours (Energy C. , 2012). Small CAES technology would dramatically lighten the loads on networks, help people who cannot connect to a power grid and serves as an advantage to those people living in developing countries.

A main goal of dissertation was to produce some correlation between the theoretical analysis and the data from dyno testing. The isothermal and adiabatic equations used are 'ideal' equations which are never actually achieved by physical machines. It was found that the dyno results were substantially lower than the ideal equations which were used to calculate the stored energy and specific power. This is because the theory does not take into account losses like compressor mechanical and storage tank thermal losses, compressor and air motor thermodynamic efficiency, air motor mechanical efficiency and friction and flow losses.

It is said that the most common solution for small to medium storage is batteries, although very good at storing energy they are very hard to recycle and are very dangerous if not used correctly. Yet the benefits of compressed air over electric storage are the longer lifetime of pressure vessels and materials are entirely benign as well as life time costs are potentially lower.

Like solar energy, air is a clean and an abundant resource with specific gas characteristics, which allows it to be compressed and expanded without any effect apart from the exchange of heat with the immediate environment. This heat energy could be captured and used for heating our homes, for hot water, cooking or even generating electricity. Thus, CAES is a simple and effective way of storing energy for later use.

With a renewable energy target of 20% or 45,000 Giga Watt hours (GWhr) by 2020, there is no better time like the present to harness the energy to provide a cleaner future for our children's children.

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ENG 4111 Research Project Part 1

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ENG 4112 Research Project Part 2

Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

K.Herriman

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Acknowledgements

During the past eight year studying with the Lectures and Staff of University of Southern Queensland I could not have asked for a more respectable group of professionals to guide me though my engineering degree. The knowledge and experience they have given me, not only is invaluable but also transferable in any aspirations that I have.

I would like to thank my supervisors for this dissertation, Dr Leslie Bowtell and Dr Ray Malpress. Their willingness to share their vast technical knowledge and provide guidance where necessary, allowed me to further my knowledge and successful complete this dissertation. I appreciated all the time and effort you have given me throughout this year.

Finally, I am dedicating this work to the most important people in my life; my family, in particular my wife Sarah and daughter Sophie. Sarah at (many) times, has come second to my studies, she has witnessed all my highs and lows throughout these past eight years but at every stage, she has believed in me when I may have doubted my own work. I must say thank you to her for having patience with me during this time and also bringing our daughter Sophie into this world. Love you.

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Acronyms

A	Amps
AC	Alternating Current
CAES	Compressed Air Energy Storage
CFM	Cubic Feet per Minute
dB	Decibels
DC	Direct Current
HCAES	Hybrid Compressed Air Energy Storage
J	Joules
K	Kelvin
kW	Kilowatt
kWhr	Kilowatt Hour
kPa	kilopascals
kg	Kilograms
L	Litres
Li-Ion	Lithium Ion
m	Meters
mm	Millimeter
mA	Milliamps
m^3	Meters Cubed
MJ	Megajoules
MW	Megawatt
Nm	Newton meters
P	Power
Pa	Pascal
PSH	Peak Sun Hours
PV	Photovoltaic
R	Universal Gas Constant
RPM	Revolutions per Minute
SCAES	Small Compressed Air Energy Storage
W	Watts
V	Voltage

Symbols

τ	Torque
γ	Gamma
ω	Angular Velocity

CHAPTER 1

1. INTRODUCTION

1.1. Background

Australia has a sparse population, peaky energy demand profile and extensive untapped renewable energy resources. The energy sector understands that continuing on the path of traditional power generation and transmission / distribution system augmentation is becoming ever-more expensive (Consulting, 2012). The situation is seemingly right for the broad scale adoption of alternatives such as energy storage.

With a projected population of 35.9 million by 2050 and the total projected energy consumption of almost 35% by 2030 (International, 2010) (Figure 1),

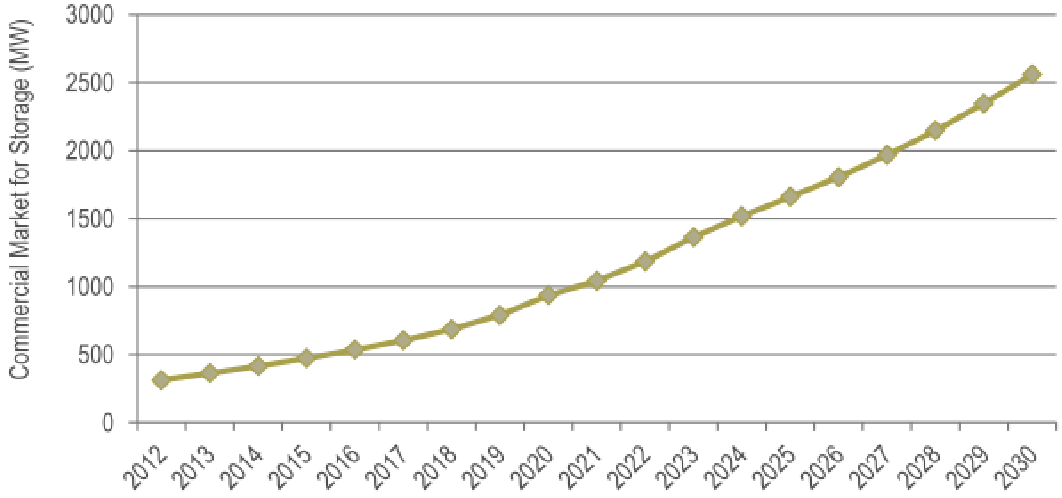


Figure 1 - Total Forecast Commercial Market for Energy Storage in Australia (Consulting, 2012)

We need to take charge of our futures energy needs now and find more viable alternative solutions though the storage of wind, solar, tidal and ocean energies, which Australia has been fortunate enough to have an abundance of (Figure 2). This rich diversity of renewable energies may one day contribute substantially to a future with 100% renewable electrical energy.

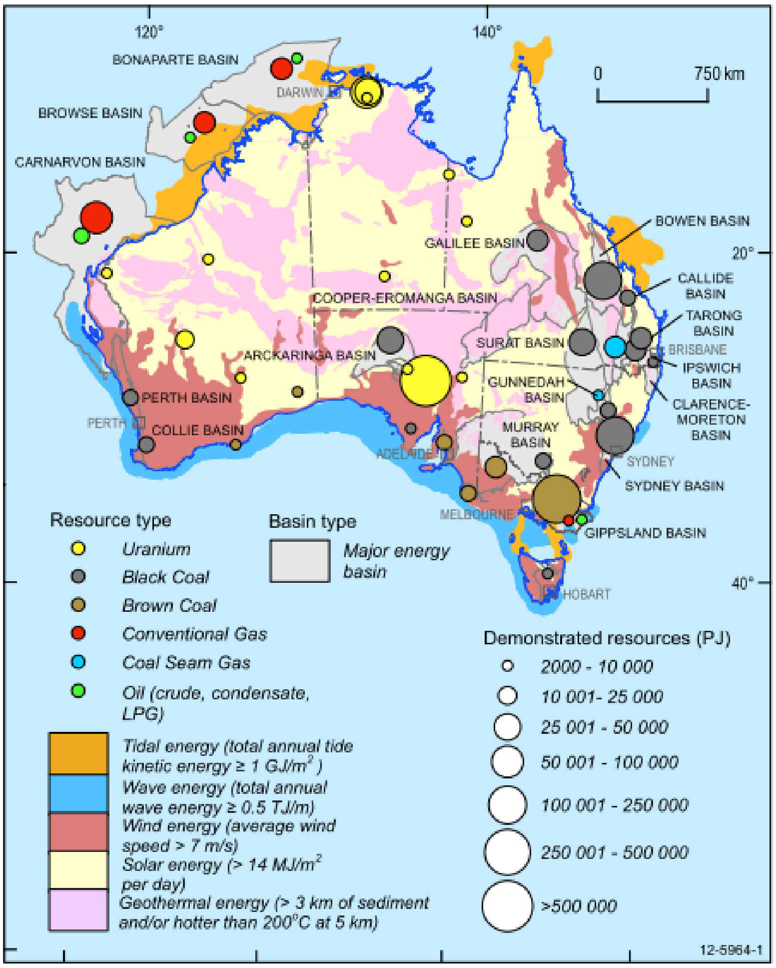


Figure 2 - Australia's Energy Resource (Australia G. , 2011)

Electricity supply can be divided into four stages: generation, transmission, distribution, and retail. Although there is a growing base of renewable energy supply in Australia (e.g. wind, hydro, solar) most electricity is generated by burning fossil fuels (e.g. coal, gas and oil) at large scale conventional power stations (Consulting, 2012)

These generators, and their fuel, are typically located a long way from where the electricity is consumed. Moving electricity across these long distances therefore requires a capital-intensive transmission network to deliver electricity to substations located near demand centers.

Balancing electricity supply and demand at all times becomes more challenging in power systems with higher levels of renewable generation. Inevitably, a significant part of the renewable energy supply will be intermittent, depending on weather conditions that are variable on several time scales.

In an article from The Australian “Rooftop solar panels overloading electricity grid” it was reported that feeding so much solar power back into the network is stressing the system and causing voltage rises which could damage household devices. In addition to this a spokesman from Energex told The Australian that “it is becoming more difficult for electricity distribution authorities to set up the power system to ensure correct voltages (Hepworth, 2011).

The interest in renewable energies is increasing, which is evident with hydro power in the Snowy Mountains, wind farms in Victoria, South Australia and Queensland, geothermal energy in South Australia, wave power in Victoria and solar farms in all states. But with all these renewable energies there is still one problem… ***Storage***…

But why are we always thinking on such a large scale?

In Australia there is a potential to transform 6,630,554 private dwelling (consisting of separate houses, semi-detached, terrace houses or townhouses) (Statistics, 2013) into small scale energy storage stations. This would give the consumers, in this case the occupants; the power to flick a switch and use stored energy to power their homes and alleviate stresses on the electrical network and not to mention save money.

1.2. What is Power and Energy

Before exploring how to store energy there are two terms, which definitions need to be clarified; these are ***Power*** and ***Energy:***

Power *is the rate of which work is done in Watts (W)*

&

Energy *is the potential to do work in Joules (J).*

It should be noted that electrical energy is not "stored" in an electrical network as water or gas is stored in pipes which transports it. Energy is produced by the movement of electrons in a current; when an appliance is switched on, energy is instantly transmitted to it from the generator (via this current) at close to the speed of light. If the generator were to be turned off the current would instantly stop.

1.3. What is Compressed Air

Compressed air is a form of stored energy that is used to operate machinery, equipment, or processes. Compressed air is used in most manufacturing and some service industries, often where it is impractical or hazardous to use electrical energy directly to supply power to tools and equipment.

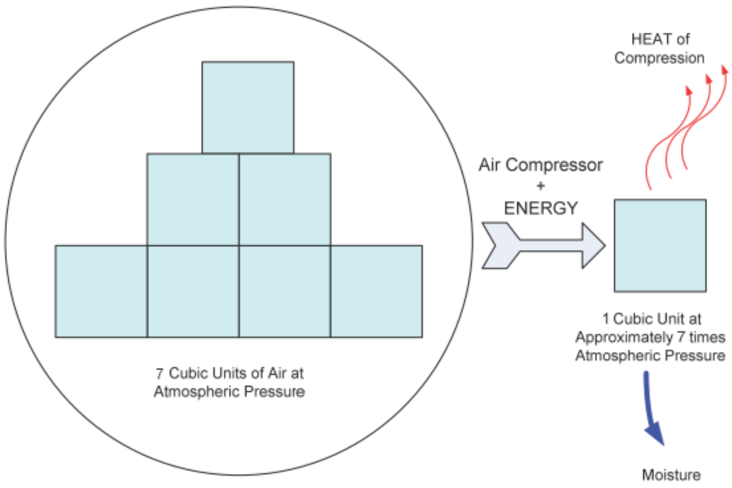


Figure 3 - Conversion of Atmospheric Air into Compressed Air

Powered by electricity, a typical air compressor takes approximately seven volumes of air at atmospheric conditions, and squeezes it into one volume at elevated pressure (about700 kPa). The resulting high pressure air is distributed to equipment or tools, where it releases useful energy to the operating tool or equipment as it is expanded back to atmospheric pressure. (Cunha, 2012)

It's important to remember that compressing air involves two different variables which are ***Pressure*** and ***Volume*:**

Pressure (kPa) *is the measure of how hard the air is pushing against the inside of whatever it is contained in.*

&

Volume (m^3) *determines how much air will fit inside of a container*

1.4. **Compressed Air Energy Storage (CAES)**

Compressed air energy storage is a developing technology that has the potential to meet the needs of intermittent sustainable energy sources and high peak load electrical power demands. With a very long service period, low cost of energy, low cost of maintenance and operation, and high power efficiency the CAES power plant produces power by storing energy during off peak periods (Das & McCalley, 2012). This is done in the form of compressed air and used on demand during the peak periods to generate power with a turbo generator / gas turbine system.

This is not an unproven technology and on a large scale there are two existing CAES plant in the world. The first plant ever built was in Huntorf Germany, which was commissioned in 1978 and capable of producing 321 MW for two hours. The second was in McIntosh Alabama USA, which was commissioned in 1991 and capable of producing 190 MW for 26 hours (Energy C. , 2012).

The design behind a CAES system is to use electric power to run compressors that compresses air into a tank / reservoir at very high pressure, and then the air is used under pressure, to turn a turbine creating power on demand (Figure 4).

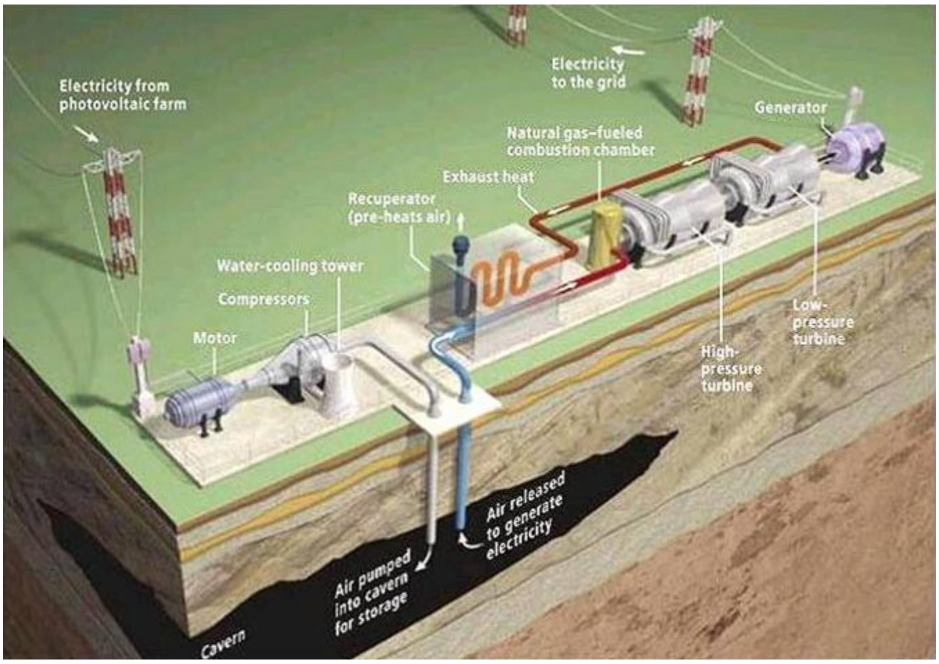


Figure 4 - Compressed Air Energy Storage Plant

1.5. **Project Aim**

To investigate the feasibility of using a Small scale Compressed Air Energy Systems (SCAES) in a domestic household application i.e. to offset the peak demand air conditioning places on local distribution networks and household economies.

1.6. **Project Objectives**

1. Research the existing literature on renewable energies and in particular CAES.
2. Design a CAES as a storage and regeneration plant for a domestic household using off-the-shelf componentry.
3. Identify all alternatives for the primary energy generation system. PV, wind, solar thermal etc.
4. Investigate direct air compression from the primary energy source, e.g. wind turbine driven compressor.
5. Identify efficiency of energy transfer of the various options
6. Identify cost effective componentry that matches the system requirements
7. Create a computational model to assist in system design and optimization
8. Use the model to analyse the potential for CAES to be employed as a cost effective functional alternative energy storage and regeneration system for domestic households.

As time and resources permit:

9. Implement the CAES design using off-the-shelf componentry into a domestic household application to confirm design and results

1.7. Overview of the Dissertation

This dissertation is organized as follows:

Chapter 2 – Shows the outcomes of literature reviews conducted on CAES, SCAES and hybrid system. It explains the energy storage mediums which are currently being used throughout the renewable energy sector and where CAES are currently being used energy storage.

Chapter 3 – As heat is generated from compression is it important to understand the thermodynamic behind an ideal system and how heat relates to energy and work. In this chapter the ideal gas law is explained and the difference between isothermal and adiabatic process.

Chapter 4 – Outlines what is required from an ideal energy source and explains how the efficiency of the system is calculated. In addition to this an overview is given of the SCAES system for this dissertation and how dynamometer testing was conducted.

Chapter 5 – Presents and discusses the results of the theoretical analysis and practical dynamometer testing. The data is then compared to that of the storage technology of batteries.

Chapter 6 – Provides a discussion on the SCAES system and goes into depth on the systems efficiency and compares to other equipment. Other renewable energy alternatives are discussed as the primary energy sources and whether they can drive a compressor directly.

Chapter 7 – Presents the project conclusion, improvements to the system and future works.

CHAPTER 2

2. COMPRESSED AIR ENERGY STORAGE

2.1. Introduction

In order to better understand contemporary CAES 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 selected textbooks on energy storage available in academic libraries.

In carrying out the review it was found that there were concerns with the following:

1. The amount of losses within a system which decreased efficiencies. These losses were mainly associated to the heat of compression.
2. The physical size of receiver for the hours of energy storage required.

2.2. Energy Storage Technologies

Energy storage is a well-established concept yet still relatively unexplored (Connolly, 2010). A number of very different methods exist to store "electric energy," some of which are listed in Figure 5.

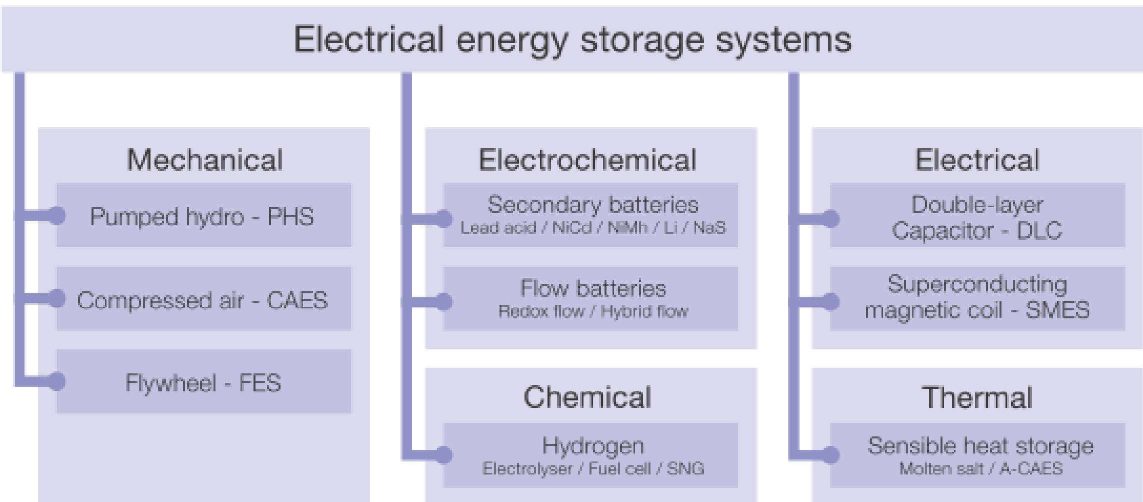


Figure 5 - Classification of Electrical Energy Storage System According to the Energy Form

Only two of those shown actually store the energy in electric form: super-capacitors and superconducting magnetic energy storage, which keep the energy as electric charge or magnetic fields respectively. These storage technologies can also be compared in terms of power quality and discharge time as seen in Figure 6.

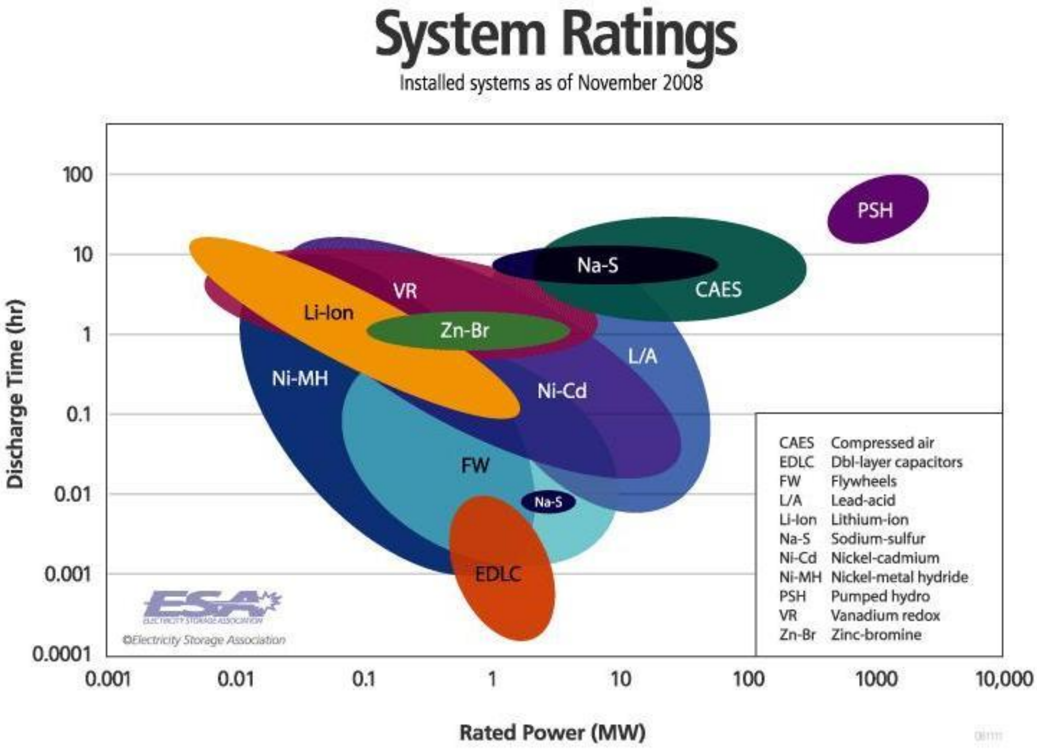


Figure 6 - Comparison of Various Storage Technologies in Terms of Power Capacity and Discharge Time (Association, 2011).

Most energy storage systems require the useful energy to be converted from its initial state into another form which is more suitable for storage. When ready to use it is then converted back into a useful form. In each conversion there is a loss associated with the efficiency of the conversion process, and a comparison of several energy storage methods should take the full turn around efficiency of the storage method into account.

Batteries actually store the energy in a chemical form, but the natural operation of the battery converts the power to direct current electric power upon being provided with a pathway for the power to flow. Mechanical storage includes several types of flywheels, compressed air and pumped hydro systems. Thermal storage systems use electricity to heat a liquid to very high temperatures and then use that, via a heat exchanger, to heat steam to drive a steam turbine generator or a sterling cycle generator (Willis & Scott, 2000).

Energy storage systems have always had the back seat when generators can produce energy in real time as it is being consumed. The large upfront costs of building storage system and the cost associated with energy losses that occur in converting the energy from one form to another for storage has made it hard for energy storage to compete.

2.3. **Conventional Compressed Air Energy Storage (CAES)**

The CAES technology consists of converting excess base load energy into stored pneumatic energy in pressure vessels or underground caverns by means of a compressor for later release though a gas turbine as premium peaking power (Vadasz, 2009).

During compression, heat is generated which is removed before it is stored. This heat energy can be stored in thermal energy storage for use at a later stage. In a power plant with a standard gas turbine, approximately two-thirds of the gas is used to compress the air. It therefore makes sense to use off-peak electrical power to pre-compress the air, and later use the compressed air in the gas turbines when the turbines are producing electricity during peak hours. In this way, three times the power is produced for the same fuel consumption (Primm, 2011).

Three different types of underground cavities have been considered for CAES; excavated salt domes because salt self-seals under pressure, cavities in rock formations (either natural or excavated) and aquifers. Due to the limited availability of natural locations, sites can be costly and the stability of any cavern to withstand cycling temperature and pressure must be fully tested and understood (Primm, 2011).

2.4. **Where is it Being Used**

Currently two CAES plants are operational in the world, one in Huntorf, Germany, and the other in McIntosh, Alabama, USA. Both plants use excavated salt domes for storage.

Table 1shows that the McIntosh plant has a lower total amount of energy per unit output, but this is a new plant with a recuperator which utilises the waste heat in the turbine exhaust gases to preheat the compressed air entering the turbines (Primm, 2011).

Table 1 - Comparison of Existing CAES Plants

	Huntorf, Germany (Energy C. , 2012)	**McIntosh, USA** (Energy C. , 2012)
Date of Commissioning	1978	1991
Storage	Two cylindrical salt cavern, each with $150{,}000 m^3$ at a depth of $600 - 800 m$	One salt cavern $538{,}000 m^3$ at depth of $450 - 750 m$
Output	321 MW over 2 hours	190 MW over 26 hours
Energy Required for 1 kWhr of Electricity	0.8 $kWhr$ electricity, 1.6 $kWhr$ gas (Total 2.4 $kWhr$)	0.64 $kWhr$ electricity, 1.7 $kWhr$ gas (Total 2.04 $kWhr$)
Pressure Tolerance	$50 - 70\ Bar$	$45 - 76\ Bar$
Efficiency	42% | 60%	54% | 75%
Remarks	World's first CAES plant	First CAES plant with recuperator

Calculating the efficiency of a plant, care should be taken over the value of input energy, particularly the value placed upon gas. The simplest method is to give gas the same value as electricity; in this case the efficiency of Huntorf (which requires 0.8 $kWhr$ electricity and 1.6 $kWhr$ gas for an output of 1 $kWhr$ electricity) would be $\frac{1}{0.8 + 1.6} = 42\%$ and the efficiency of McIntosh would be 54%. However, 1 $kWhr$ of gas cannot simply be converted into 1 kWhr of electricity – if 1 unit of gas is used in a combined cycle gas turbine with a realistic efficiency of 55%, only 0.55 $kWhr$ electricity will be generated. Using this 55% efficiency, the efficiency of Huntorf becomes $\frac{1}{0.8 + 0.55} \times 1.6 = 60\%$ and the efficiency of McIntosh becomes 75% (Primm, 2011).

2.5. **Small Scale Compressed Air Storage System (SCAES)**

SCAES is the same concept of the larger CAES system just on a small scale. This technology would dramatically lighten the loads on networks, help people who cannot connect to a power grid and serves as an advantage to those people living in developing countries.

Dominique et al investigated the possibility of, off the gird CAES system which uses photovoltaic (PV) panels as the energy source. Specific details of the paper were the development of PV-CAES systems that can be operated at very low powers to optimally utilise the output of individual PV panels.

To achieve this, a single stage isothermal compression system running at $10 - 60\,RPM$ that utilises a fluid piston was designed and examined. Focus was on achieving high efficiencies that can utilise the entire range of the electrical output of a standard residential $160\,W$ PV panel, which may not be conducive for operating commercial compressors.

An advantage of the hybrid system was that there would be a decrease in energy losses. This is due to the reduction in the number of moving parts / components required for the multistage conversion of solar energy to compressed air to powering household units.

The hybrid system employs a fluid piston which increases volumetric efficiency as well as reduce dead volume, which corresponds to the clearance between piston radius and outlet.

For different stroke lengths the liquid volume was varied and pressures monitored. In a closed system the increase in fluid amount leads to an increase in final pressure due to the consequent decrease in "dead volume". The compression speed ranged from $6 - 63\,RPM$ and at $15\,RPM$ a maximum of $25\,W$ was achieved. At $15\,RPM$ it took two hours to fill a $18\,L$ at $10\,Bar$ as an open system had an efficiency of 60%. This was lower than their designed closed system that recorded efficiency of 70% at $3 - 7$ Bar.

Paloheimo et al have studied CAES for portable electrical and electronic devices like mobile phones and rural off grid connection which would help developing countries.

Assessments were made on renewability efficiency and compared the storage mediums with the likes of batteries. During the course of the study it was obvious that different types of storage equipment use different principles and therefore a direct comparison of storage mediums tends to be very complex. For comparison between storage systems the following parameters were used; overall efficiency, optimal power output and stored energy.

For some comparisons compressed air was said to have between $40 - 70\%$ efficiency and an unlimited power output whereas Li-Ion battery has an efficiency of $90 - 95\%$ and $140 - 300\ \frac{Whr}{kg}$ (Paloheimo & Omidiora, 2009).

It was said that the benefits of compressed air over electric storage are the longer lifetime of pressure vessels compared to batteries and the materials are entirely benign as well as the costs are potentially lower. But the costs for production of advanced pressure vessels are still high. On the other hand, batteries provide nearly constant voltage over their entire charge level, whereas the pressure of compressed air storage varies the charge level (Paloheimo & Omidiora, 2009).

Paloheimo et al focussed on micro turbines running a plain pressurised air. The electrical output generated was $16\ W$ at $1\ Bar$ but required a speed of $100{,}000\ RPM$. The maximum total efficiency from compressed air to electricity was 10.5% at this speed.

During an electrical energy Vs volume test it was found that overall conversion efficiency was assumed to be 16% for a volume of $300\ dm^3$. With these results it was assumed that a pressure of $61\ Bar$ is needed to obtain $5.5\ Whr$ of energy, which in theory is limited to $3.3\ Whr$ due to air flow. Therefore to reach $34.6\ Whr$ of power would take 40 minutes to fill, this is not taking into account the additional losses which would occur from pumping.

It was identified that the power density was limited by the maximum speed of the ball bearings and main losses were from the blade profile losses and exit losses. At higher speeds the exit losses were reduces and therefore efficiency did increase along with power density.

An overview of a mini scale compressed air storage system was reviewed by Khamis et al. The analysis was focusing on the output pressure from the air compressor unit that can be used to generate electricity at the generator. They identified that the main advantaged of mini CAES would be peak shaving, spinning reserve VAR support and arbitrage.

The disadvantages were associated with energy conversion losses that are inevitable. It was estimate that 1 kWhr worth of natural gas would be needed for every $3\ kWhr$ generated from CAES system.

Using off the shelf equipment Khamis et al used an air compressor with a $270\ L$ tank and maximum working pressure of $11\ Bar$, a micro turbine rotating at $800\ RPM$ connected to a $24\ VDC$ generator. It was found over testing that if the input air was varied from $4\ Bar - 8\ Bar$ that the output voltage was dependent on the input air pressure. At $7\ Bar$ the system was able to produce $12\ VDC$.

According to their results the $270\,L$ tanks released at $1\,Bar$ would last for 30.12 seconds and $7\,Bar$ lasted 6.3 seconds. Khamis et al concluded that when the level of pressure was increased the time taken to use the reservoir was shortened. Further analysis of the DC generator found that the output voltage produced was proportional to the speed of the micro turbine.

Khamis et al also found that the system built was capable of producing $6 - 8\,VAC$ output instead of the desired $12\,VAC$; this was due to the low input air pressure entering the micro turbine.

According to Taylor et al analysis of compressed air energy storage renewable energy sources on power grids is creating a significant challenge for the electricity industry.

This fluctuation is dependent on the penetration of renewables, the size of the grid and the availability of other power sources such as gas turbines, open cycle gas turbines or hydro. This is expected to become worse as the level of installed renewable energy increases. To overcome this “smart” energy grids with improved metering and increased demand control are expected to be the solution.

Their technical analysis identified three generations of CAES plants.

First generation (Figure 7) refers to a conventional plant which comprises of both compression and generation components. The first operational system was Huntorf, Germany in 1979 and the second was McIntosh, Alabama in 1991.

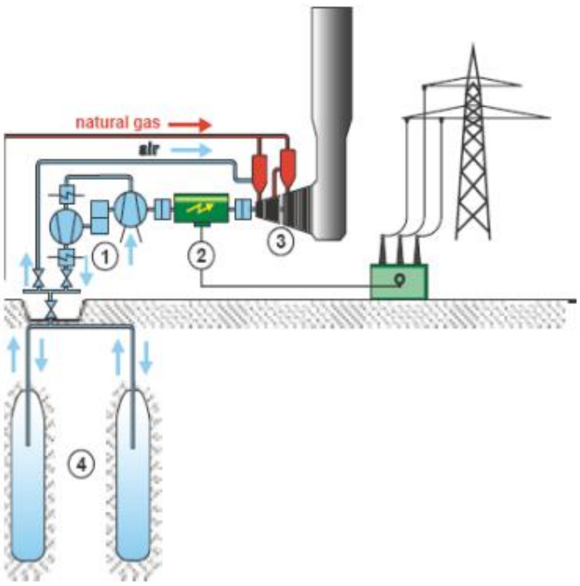


Figure 7 - First Generation (Taylor & Halnes, 2010)

Second generation (Figure 8) is very similar to the first however advancements were made in technology and turn around efficiencies are approximately 54% compared with 48 – 50% for a first generation system.

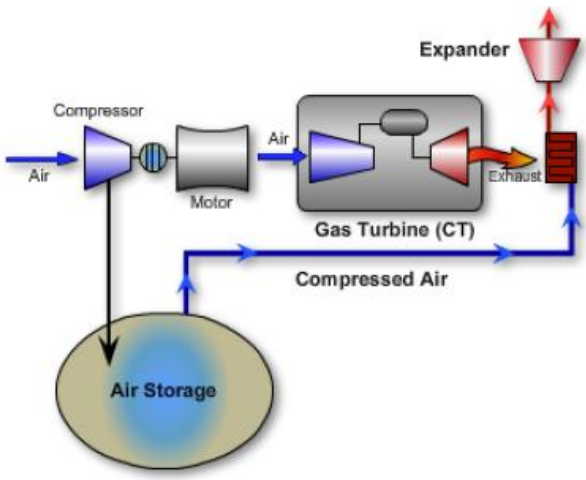


Figure 8 - Second Generation (Taylor & Halnes, 2010)

Third generation (Figure 9) or adiabatic CAES system does not use natural gas in the generation process (as the latest design uses molten salt heat storage, heated with solar thermal power generators). This system stores the heat of compression which is re-used during generation to warm the compressed air. One benefit of this generation is zero carbon emissions as there is no fuel consumption required in the turbine section.

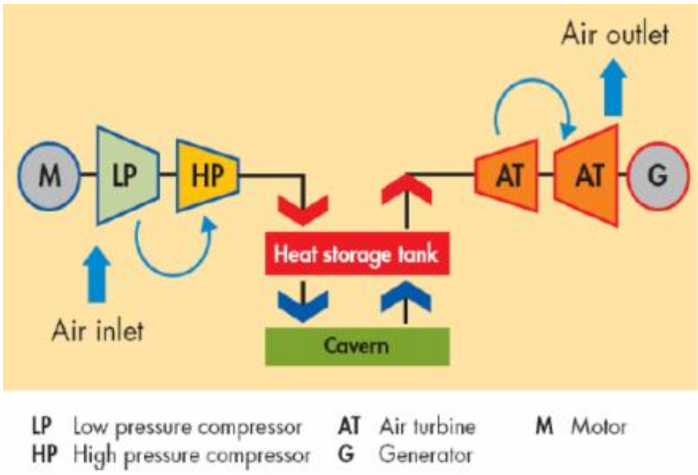


Figure 9 - Third Generation (Taylor & Halnes, 2010)

Large CAES plants require a suitable sealed underground cavern for air storage as above ground vessels do not have the scale necessary. It has been found that the mined salt rock caverns are the best option for storage, while aquifers and abandoned mines and depleted oil and gas fields are promising. Salt cavern for CAES operated between $40 - 100\ Bar$. These pressures result in the cavern being contained between $450\ m - 800\ m$ deep and a volume of $150{,}000\ m^3$ or $538{,}000 m^3$

Varin Vongmanee conducted a study on the renewable energy applications for uninterruptible power supply based on compressed air energy storage system. The study used wind energy to produce the compressed air power via a compressor.

Varin states ‘because wind power is primarily uncontrollable as an energy source it requires a CAES plants to store wind energy. Which then can be distributed during power outage, used during peak hours or peak shaving, or when energy is needed and cost of energy is high’.

As wind energy is kinetic energy and requires large masses of air moving over the earth’s surface. The wind turbine receives kinetic energy that is transformed to mechanical or electrical forms depending on end use.

The simulation results show that the compression and expansion pressure directly depends on air flow rate and system efficiency. With improvements to the system efficiency of thermodynamic conversion, the system should be able to operate by increasing pressure ratio of compression, or increasing the pressure of expansion power.

Although more stages can increase efficiency, the system is complex and incurs high initial and maintenance cost. His proposed simulation results could be used for backup power system and peak shaping for energy management applications.

CHAPTER 3

3. THERMODYNAMICS

3.1. Introduction

Thermodynamics can be defined as the science of energy. The name thermodynamics stems from the Greek words *therme* (heat) and *dynamis* (power), which is most descriptive of the early efforts to convert heat into power (Yunus Cengel, 2002).

In both large and small scale CAES system energy storage is done by compressing air adiabatically or isothermally. This chapter gives an introduction into the equations used when calculating energy from air and energy density.

3.2. Adiabatic Compression of Air

An adiabatic system is one which is thermally insulated from its surroundings therefore heat is neither supplied nor rejected. (R.K.Rajput, 2007). The heat generated during the compression cycle is stored as thermal energy and then released during expansion to increase the flow of air though the outlet.

3.3. Isothermal Compression of Air

An isothermal process is a change of a system during which the temperature remains constant (R.K.Rajput, 2007). Isothermal processes occur when the system is thermally connected to a constant-temperature external reservoir, and when the change in the system is happening so slowly that the system continually maintains the same temperature as the external reservoir through heat exchange.

3.4. **Ideal Gas Law**

The ideal gas law tells us that the absolute pressure of an ideal gas is given by

$$PV = mRT$$

Where P is pressure in kilopascals (kPa), V is the volume of the gas in cubic meters (m^3), m is the mass of the substance in kilograms (kg), R is the universal gas constant in kilojoules per kilogram-Kelvin ($\frac{kJ}{kg.K}$), and T is the absolute temperature in Kelvin (K) (Pauken, 2011).

In the isothermal process, T remains constant and so the numerator of equation also remains constant. As a result, for an isothermal process:

$$PV = constant$$

This shows that at constant temperature the volume occupied by a fixed amount of gas is inversely proportional to the pressure on the gas (Harrison).

This relationship is known as Boyle's Law.

The work done in the isothermal expansion from stored volume V_i to volume V_f is:

$$W_{i\to f} = \int_{V_i}^{V_f} PdV = \int_{V_i}^{V_f} \frac{mRT}{V} dV = mRT \int_{V_i}^{V_f} \frac{1}{V} dV = mRTln\frac{V_f}{V_i}$$

As shown in the above equation, the product PV remains unchanged for an ideal gas

$$\frac{V_f}{V_i} = \frac{P_i}{P_f}$$

undergoing an isothermal process, so:

$$W_{i\to f} = mRTln\frac{V_f}{V_i}$$

$$W_{i\to f} = P_iV_iln\frac{P_i}{P_f} = mRTln\frac{P_i}{P_f}$$

To calculate the energy available in a store of compressed air that is to be expanded isothermally, we let P_i and V_i be the pressure and volume of the air in the store and P_f be the pressure of the expanded air (atmospheric pressure if all the available energy is taken out of the compressed air by the expansion machinery) (Primm, 2011).

An adiabatic process is a change of a system during which no energy enters or leaves the system through heat exchange. A purely adiabatic process can only occur if the system is thermally insulated from the surroundings. The pressure and volume of an ideal gas undergoing a reversible adiabatic process are related by:

$$PV^{\gamma} = constant$$

Where γ is the adiabatic index of the gas, given by:

$$\gamma = \frac{C_p}{C_v} = \frac{\alpha + 1}{\alpha}$$

C_p is the fluid's specific heat capacity at constant pressure, C_v is the specific heat capacity at constant volume, and $\alpha = \frac{5}{2}$ for a diatomic gas and $\alpha = \frac{3}{2}$ for a monatomic gas. Air is essentially a diatomic gas, so we use $\alpha = \frac{7}{5}$.

In calculating the net work input in the adiabatic compression of air from atmospheric pressure P_i to storage pressure P_f, we must include the work associated with moving the air from the atmosphere into the compression volume ($-P_{in}V_{in}$) and discharging the high pressure air ($P_{out}V_{out}$), causing the integration for work to become $\int VdP$, rather than $\int PdV$.

If the compressed air is preheated to the temperature it has after compression and then expanded adiabatically, is equal to the network input in the compression. From equation

$$PV^{\gamma} = P_i V_i^{\gamma} = K\ (Constant)$$

Which can rearrange to obtain the Pressure:

$$P = \frac{K}{V^{\gamma}}$$

So in an adiabatic process the net work done by the system is given by:

$$W_{i\to f} = \int_{V_i}^{V_f} PdV = K\int_{V_i}^{V_f} \frac{dV}{V^{\gamma}} = K\left[\frac{V^{-\gamma+1}}{-\gamma+1}\right]_{V_i}^{V_f}$$

$$\Rightarrow \frac{K}{1-\gamma}\left[V_f^{1-\gamma} - V_i^{1-\gamma}\right] \Rightarrow \frac{K}{1-\gamma}\left[\frac{1}{V_f^{\gamma-1}} - \frac{1}{V_i^{\gamma-1}}\right]$$

$$K = P_f V_f^{\gamma} = P_i V_i^{\gamma} = \frac{1}{\gamma - 1}\left[\frac{P_f V_f^{\gamma}}{V_f^{\gamma-1}} - \frac{P_i V_i^{\gamma}}{V_i^{\gamma-1}}\right]$$

$$W_{i \to f} = \frac{P_f V_f - P_i V_i}{\gamma - 1} = \frac{RT_f - RT_i}{\gamma - 1}$$

The final absolute temperature of a gas undergoing an adiabatic process is as followed

$$T_f = T_i \left(\frac{P_f}{P_i}\right)^{\frac{\gamma-1}{\gamma}}$$

In practice, purely isothermal or adiabatic processes cannot occur because there is no such thing as a perfect conductor or insulator. Processes can be very close to purely isothermal or adiabatic, and we use the equations describing purely isothermal and adiabatic processes as means to calculate lower and upper bounds on the amount of energy available in a store of compressed air:

Isothermal expansion at atmospheric temperature is the lower bound, and adiabatic expansion from the temperature of the air after adiabatic compression (so leaving the expander at atmospheric temperature and pressure) is the upper bound.

Whether a process is isothermal or adiabatic depends upon the thermal conductivity of the system boundary and the speed at which the process occurs: a very quick process, in which little heat is transferred between the system and its surroundings, may be considered adiabatic, and a very slow process, in which the system’s temperature remains constant, may be considered isothermal (Primm, 2011).

CHAPTER 4

4. METHODOLOGY

4.1. Introduction

In order to evaluate the SCAES technology and compare it to existing energy storage technologies it is important to look at what is required from an ideal energy storage system and then do an evaluation on the existing technology.

Equipment specifications for the components of the proposed SCAES design were used to develop a theoretical model of the system. The results were then compared against a practical model using off the shelf items. The SCAES system for this dissertation is proposed to be entirely renewable (Figure 10) and can be split into three distinct disciplines electrical / mechanical and pneumatic. Where by the electrical system consists of PV cells / converter, DC motor and AC generator and the mechanical / pneumatic system incorporates air compressor, receiver and an air motor.

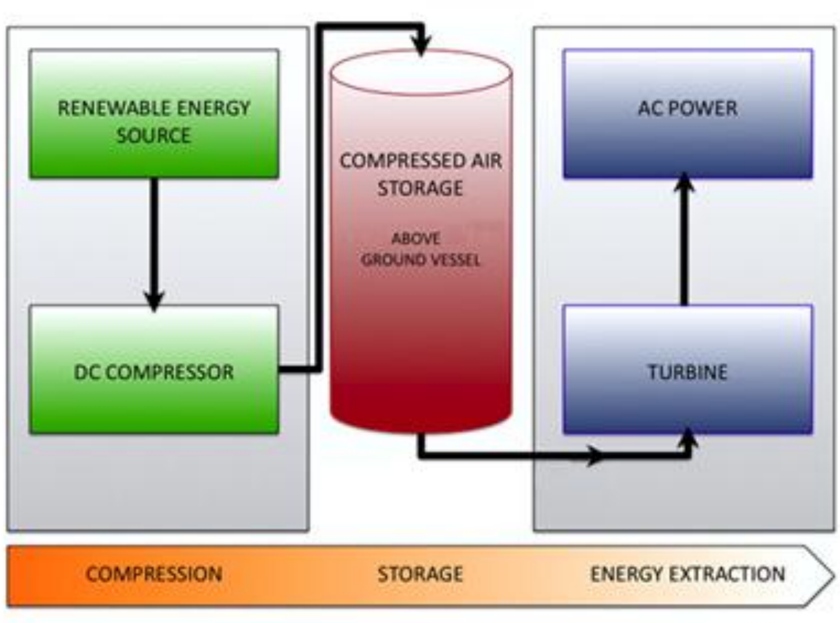


Figure 10 - Schematic of Renewable CAES System

4.2. 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 a small scale renewable energy storage system. 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.

For the purpose of this dissertation the range “Small Sized” energy storage devices are assumed to be from $1\ W$ to approx. $10\ kW$. With this in mind Figure 11 below indicates the performance of a number of commercially installed storage application with respect to their time of discharging and rated power.

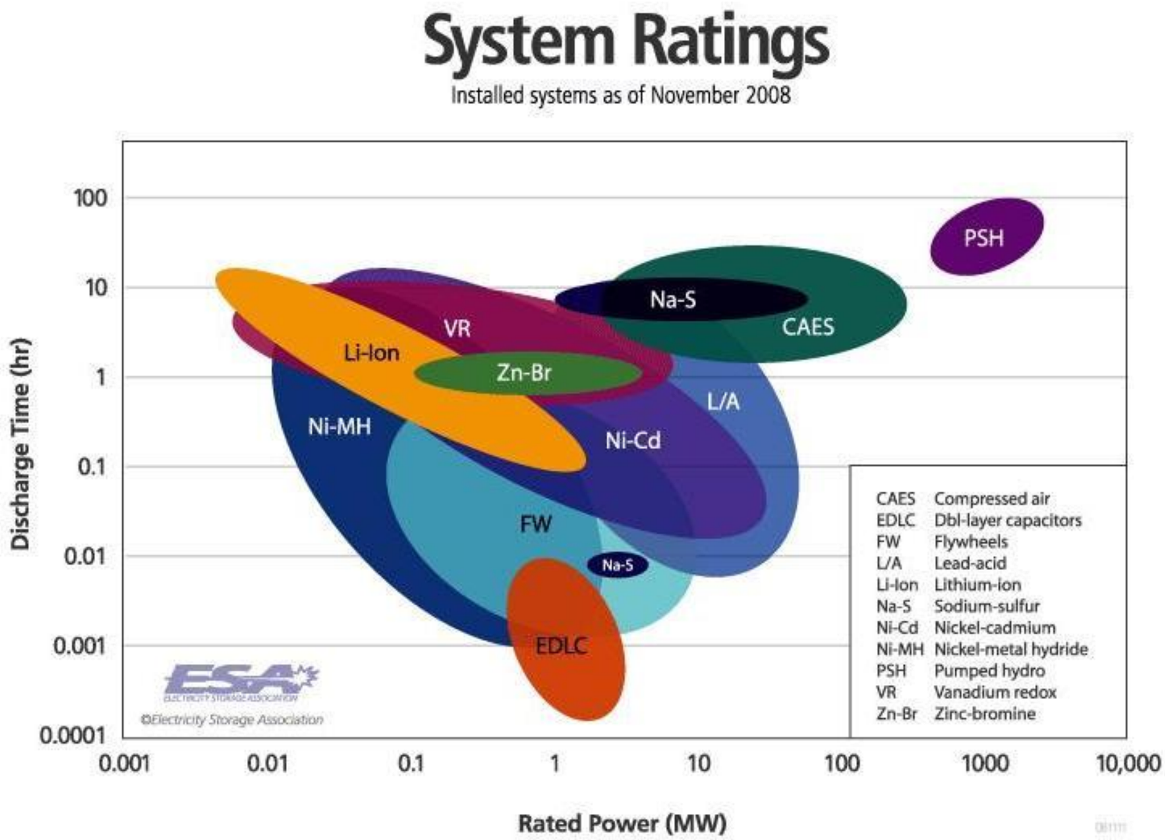


Figure 11 - Comparison of Various Storage Technologies (Association, 2011).

Based on Figure 11 the obvious technologies for small application would be

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

It must be said though that this is only based on time of discharge and rated power which does not taken into account other desirable characteristics of storage technologies.

4.3. Small Scale Compressed Air Storage

As it has been said throughout this dissertation compressed air technology is not new and has been effectively used in commercial application for many years. Some of the main advantages of compressed air are

- 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
- Can be used within a hazardous area

As with chemical batteries and hydrogen storage, the main disadvantage 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

- 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 affect 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.

4.4. **Efficiency of Conversion**

"Efficiency" in energy storage systems most often refers to how well the system uses space or weight to store energy (Willis & Scott, 2000). The efficiency of an energy device is a quantitative expression of balance between energy input and energy output and can be defined as follows:

$$Device\ efficiency\ (\eta) = \frac{Useful\ energy\ output}{Energy\ input}$$

With the conversion from one type of energy to another the conversion efficiency is never 100% and the output energy is always going to be lower than what is inputted which is evident from the equation above.

4.5. **Selected Equipment for Design**

The SCAES model was designed using off the shelf equipment to store compressed air to use as a energy source. Ideally the system would have a small footprint which is easily adaptable to any residential house without it being an eyesore. If the design is successful the system would be easy to assemble affordable and transportable.

4.5.1. **Photovoltaic Cells**

Solar energy is the cleanest and greenest source of renewable energy generated electricity. Using advanced cell technology the panel efficiency is said to be 15%. An advantage of using solar panels and a clean regulated supply is once the receivers at capacity, any excess energy generated by the panels can be fed back into the grid reducing your electricity costs and saving you money.

4.5.2. **Air Compressor Package**

AC motors are typically $85 - 90\%$ efficient or more when converting electricity into mechanical power. The size of the motor used during testing was $1.5\,kW$ and characteristically for every $746\,W$ the motor is rated to the compressor can output 4 cubic feet per minute (CFM) at $700\ kPa$ (Toolbox).

The type of compressor used was a single-acting reciprocating compressor which was air-cooled similar to that of Figure 12. These types of compressor are said to be less efficient than other types (Challenge, 2003). The compressors output was $8.8\,CFM$ and held $0.065m^3$ of compressed air in the receiver. This was confirmed by the calculations as seen in Appendix D.

Figure 12 - Air Compressor

An air pressure regulator was necessary for the air motor during testing as there needed to be at constant pressure regardless of the rise and fall of line pressure to verify the maximum efficiency profile of the air tools.

Figure 13 - Air Pressure Regulator

4.5.3. **Air Motor**

A pneumatic motor or compressed air engine is a type of motor which does mechanical work by expanding compressed air. Pneumatic motors generally typically operate at $620\ kPa$ and convert the compressed air to mechanical work through either linear or rotary motion. Linear motion can come from either a diaphragm or piston actuator, while rotary motion is supplied by either a vane type air motor or piston air motor.

Figure 14 & Figure 15 show the type of air drill which were used. Both were of rotary vane type as this is the most common air motors used in industry.

Figure 14 - Angle Drill (Air Motor)

Figure 15 - Straight Drill (Air Motor)

They operate using blades that fit into radial slots in a rotor which can be seen below in Figure 16

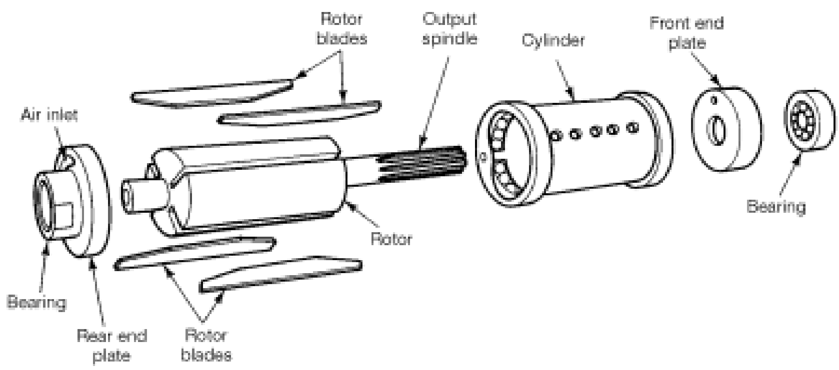
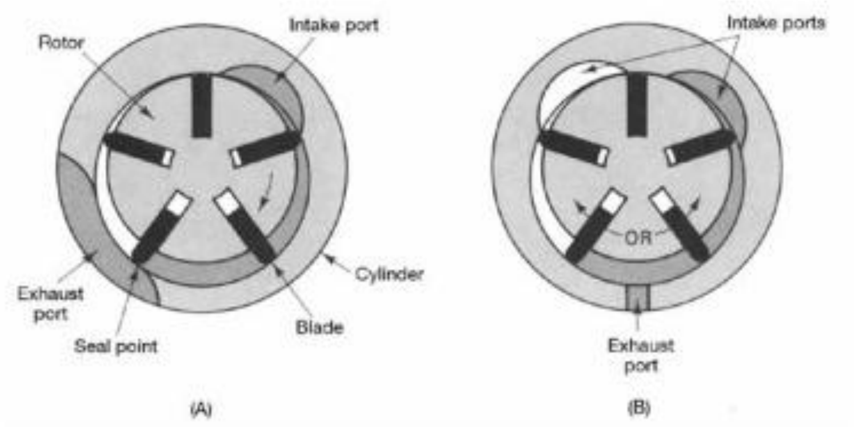


Figure 16 - Parts Which Make up a Typical Rotary Vane Motor

The rotary motion is a result of air pressure exerted against the exposed area of the blades. Thus, the force produced is transmitted through the rotor gearing to the output shaft or is transmitted directly, if no gears are used. The air is then discharged when it reaches the exhaust port (Figure 17).



(a) Single Direction (b) Reversible Direction

Figure 17 – Direction and Air Movement Thought Rotary Vane Motor

As a load is applied to such a non-governed air motor, the speed decreases and the torque and horsepower increase to a level where they match the load. As the load is increased, the horsepower produced by the motor continues to increase until the motor slows to roughly half of free speed. At this point, the motor has reached peak horsepower and will run at greatest efficiency. If the load is increased beyond this point, the torque will continue to increase to the stall point, but the horsepower will decrease.

In this design the air motor were off the shelf air drills, the drills characteristics can be found in Table 2.

Table 2 - Specification of Air Motors

	Angle Drill (Figure 14)	**Straight Drill** (Figure 15)
Chuck Capacity	3 / 8”	3 / 8”
Free Speed	1,200 RPM @ 620 kPa	2,200 RPM @ 620 kPa
Average Air Consumption	4 CFM	3.6 CFM
Noise Level	83 dB	90dB

For specific parts break down and details refer to Appendix E

4.5.4. AC Generator

Although not tested in this design it was proposed that electrical output was required. To do this a generator would be required to output a voltage which could be used though an inverter. This would ensure that the power is clean and at a usable voltage.

4.6. Model Development Flow Diagram

Figure 18 below shows a flow diagram of the equipment listed in Section 4.5 and how it's connected for the SCAES system.

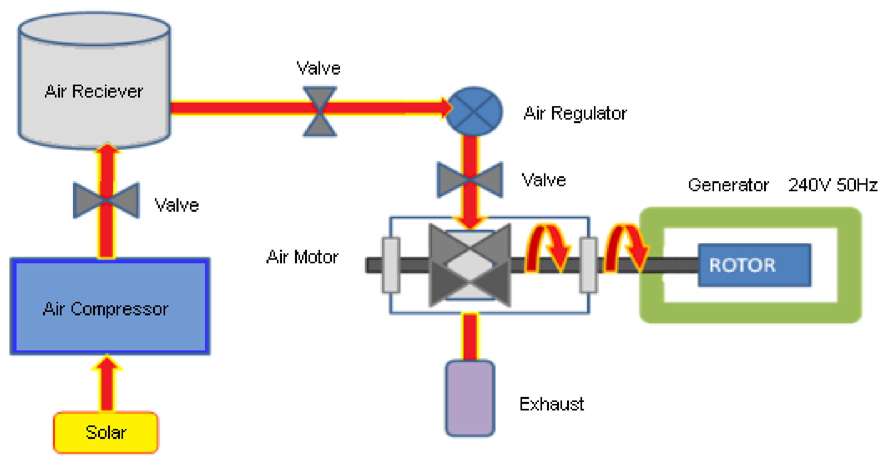


Figure 18 - Model Flow Diagram

4.7. Bench Testing System

Verification of the air compressors and air motors efficiency was a key outcome for this dissertation as the overall efficiency of a compressed air system can be as low as $10 - 15\%$ (Moskowitz, 2010)

A small dynamometer was built to test the air motors. A dynamometer or "dyno" for short is a device for measuring force, moment of force (torque), or power. As power is not directly measured but calculated from the torque, the torque needed to be found using:

$$\tau = F \times r$$

Where τ is Torque measured in Newton-meters, F is the Force applied in kg and r is the radius of the pulley. Power then can be found using torque multiplied by the angular velocity(ω) using:

$$P = \tau \times \omega$$

Where P is Power in Watts (W), τ is Torque in Newton-meters (Nm) and ω is the angular velocity in radians per second $\left(\frac{Rads}{Second}\right)$ which can be found by:

$$\omega = \frac{RPM}{60} \times 2\pi$$

Testing was performed at six different pressures: $150\ kPa$, $200\ kPa$, $300\ kPa$, $450\ kPa$, $600\ kPa$ and finally $750\ kPa$. With the air receiver at $1000\ kPa$ and compressor switched off, the air motors where run at constant torques with fixed speed near the maximum speed.

During the test the torque and speed have to be maintained until the pressure dropped below the regulated pressure. The time which the test ran and the final tank pressure (the final tank pressure should be the same as the set regulated pressure used in that test) needed to be recorded. This process was repeated for different torques and speeds at all the regulated pressures.

For each of these tests, data for power out over time gives the energy released. From the initial and final pressures in the tank, the proportion of the compressed air used can be calculated using the ideal gas law. This identifies which power setting produces the best efficiency, that is, the most energy out from the stored pressure.

CHAPTER 5

5. RESULTS FROM ANALYSIS OF PROPOSED DESIGN

5.1. Introduction

MATLAB® which is a high-level language and interactive environment for numerical computation was used to create a model to analyse the SCAES system. A main goal was to produce some correlation between the theoretical analysis and the data from the dyno. It was found that the dyno results were substantially lower than the ideal equations which were used to calculate the stored energy and specific power.

5.2. Theoretical Analysis

Isothermal and adiabatic equations are 'ideal' equations that are never actually achieved by physical machines. An actual air compressor and motor will not achieve the values that these formulae calculate.

It can be seen from Figure 19 that the isothermal equation $W_{i\to f} = mRTln\frac{P_i}{P_f}$ produces more specific energy then adiabatic equation $W_{i\to f} = \frac{P_f V_f - P_i V_i}{\gamma - 1}$. This is due to the assumption that the air stays at constant temperature during expansion. This we know to be untrue, as air drops in temperature during expansion which is evident after periods of running an air tool they tend to be cold. To keep the temperature constant, energy must be added and this is in the form of heat (adiabatic process). This heat energy is seen as work in expanding the air which is why more energy's gained from isothermal expansion.

These figures were produced using pressures, temperatures and volumes you would see on an off the shelf air compressor (Figure 12). The pressure range was from $100\ kPa$ to a maximum of $1000\ kPa$ and a receiver volume of $0.065m^3$. When using the ideal equations, knowledge of the specific gas constant for air needed to be known which is $0.287\ \frac{kJ}{kg}.K$. Temperature needs to also be converted to Kelvins (K) before solving (Appendix C).

Using the MATLAB® script *Ideal_Gas_Equations.m* (Appendix I) the energy stored in Adiabatic and isothermal compression was calculated over the entire pressure range ($100 - 1000\ kPa$). Figure 19 shows the energy which both curves have at $750\ kPa$, as this is when maximum power was achieved during dyno testing. As it was said above the isothermal equation produces more stored energy which is due to the assumption that the air stays at constant temperature during expansion.

The amount of stored energy in the isothermal process was $171\ \frac{kJ}{kg}$ and adiabatic process was $166\ \frac{kJ}{kg}$ which are indicated on the curves below. If the relationship is used that $\frac{kJ}{3600} = kWhr$ then the energy for one kilogram can be calculated to be $47.7\ Whr$ for the isothermal process and $46.2\ Whr$ for the adiabatic process.

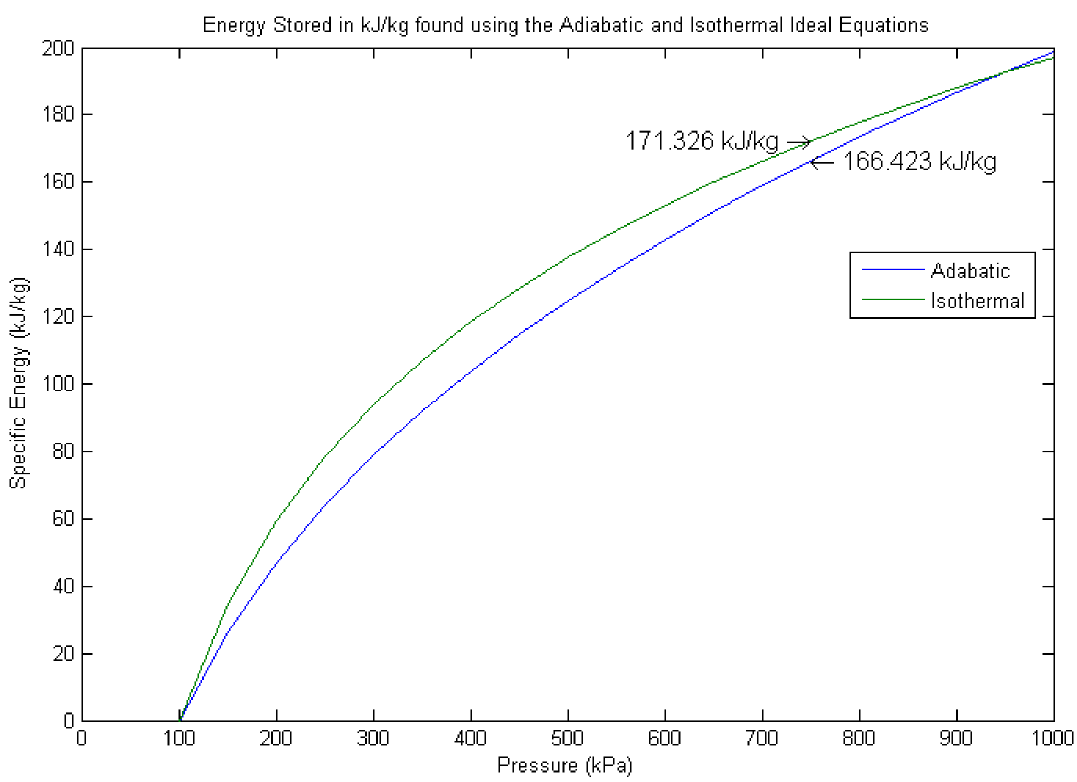


Figure 19 - Energy Stored in kJ / kg for Adiabatic and Isothermal

The ideal equations did indicate that at $950\,kPa$ that both curves stored energy would be $189\,\frac{kJ}{kg}$. This would be impractical when dyno testing as there would only be $50\,kPa$ of usable energy in the receiver if the maximum pressure was $1000\,kPa$

The ratio of the specific power which is a calculation commonly applied to mobile power sources, enables the comparison of one unit or design to another. Power-to-weight ratio is a measurement of actual performance of any power source. Figure 20 shows the specific power for both ideal equations. This is calculated using the stored energy in the compressed air divided by the volume of the receiver in liters. At $750\,kPa$ the curves show that the adiabatic specific power is significantly lower than that of the isothermal specific power for the same pressure, which was $228\,\frac{mWhr}{Liter}$ and $419\,\frac{mWhr}{Liter}$ respectively. As pressure increases to $1000\,kPa$ its indicated that more specific power per litre would be obtained from an isothermal process rather than adiabatic.

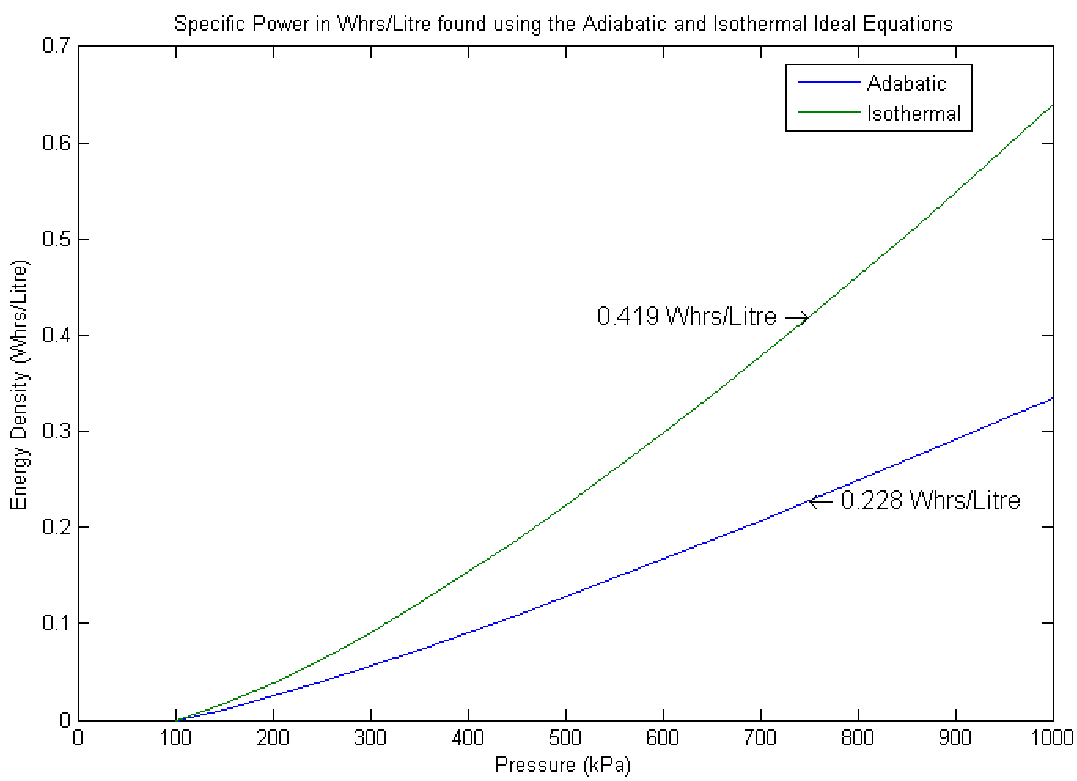


Figure 20 - Specific Power in Whr / Litre from Adiabatic and Isothermal Ideal Equations

5.3. Practical Review

To produce some correlation between the ideal isothermal and adiabatic equations in Section 5.2, a dyno test was performed (Figure 21 and Figure 22). This was done to create a performance curves for each air motors when operated at different torques for different pressures. It was found that the dyno results were substantially lower than the theoretical results, as the theory does not take into account losses like compressor mechanical and storage tank thermal losses, compressor and air motor thermodynamic efficiency, air motor mechanical efficiency and friction and flow losses.

5.4. Total Energy Compressor Used to Fill Receiver

In order to calculate the results the total energy used in pumping up the receiver from empty to full needed to be calculated. This was done using the time taken to fill the receiver and the electric motors running current. The compressor was found to draw less current when the receiver pressure was low and more current as the pressure increased. This is due to the compressor having to overcome the receiver pressure on each stroke before any air enters the receiver (Klenck, 1997).

Using MATLABs® interpolation function `interp1()` a larger number of points could be produced given a smoother plot over the whole time. The overall time which the compressor took to fill the $0.065\ m^3$ receiver was 120 seconds which worked out that the total energy which the compressor used was $54.5\ Whr$. This total energy will be used to calculate the efficiency of the system.

It is possible that this result could have been improved if the compressor was new. The compressor used had been in service for 30 years on building sites to run various air tools like drills and nail guns. The compressor had little maintenance done yet though the calculations seen in Appendix D the output was $8.5\ CFM$ which the name plate read $8.8\ CFM$.

5.5. Air Drill Dynamometer

The dyno used for testing the air tools was very simple yet effective. A set of sliding scales were fixed to the bed plate and attached to that was a section of V-belt. The maximum weight of the scales was 20 kg with increments of 0.2 kgs. This allowed for the torque of the system to be measured though a lever also attached to the bedplate. This lever was used to apply a fixed load to the V-belt in the pulley once the air drills were running.

To find the power of the air drill we must refer back to Section 4.7 where it stated that torque was a product of force multiplied by the radius of the pulley. The size of the pulley for testing had a diameter of 52 mm. Once the torque was known (which for each test the only variable was the force applied) the power could be deduced. This was done by using the torque and multiplying it by the angular velocity.

The layout of the dyno can be seen in Figure 21 and Figure 22 below.

Figure 21 - Angle Drill Dyno Test

Figure 22 - Straight Drill Dyno Test

5.6. **Maximum Efficiency Profile**

In order to find the maximum efficiency profile for each air drill a number of tests were performed. The idea was to create a profile for each regulated pressure using five or six different torques and speed settings. It was also important to record the time taken to use the compressed air from a full receiver to the set regulated pressure which would be used to find the energy that could be obtained.

The data was then entered into two MATLAB® scripts: *Test_Straight_Drill.m* and *Test_ Angle_Drill.m* (Appendix I). For each individual pressure it was seen that the power would slowly increase, peak and drop off. Where the peak occurred was the maximum output of the drill for that pressure.

When combining all these results the maximum efficiency profile for both air drills can be seen below in Figure 23. Maximum power is said to be achieved when the air motor is operating at about half its free speed and this is where they are most efficient (Air Motors, 2012) this being the case the maximum power was produced by the angle drill at $730\,RPM$ outputting $230\,W$, and the straight drill at $1280\,RPM$ outputting $463\,W$.

Looking at the specification for the straight drill in Appendix E, it states that the power output for the straight drill is $378\,W$ at $620\,kPa$, which if we compare to the straight dill air motor graphs in Figure 23 it works out to be $660\,kPa$ at $374\,W$. There was no information found regarding power output for the angle drill to make comparison.

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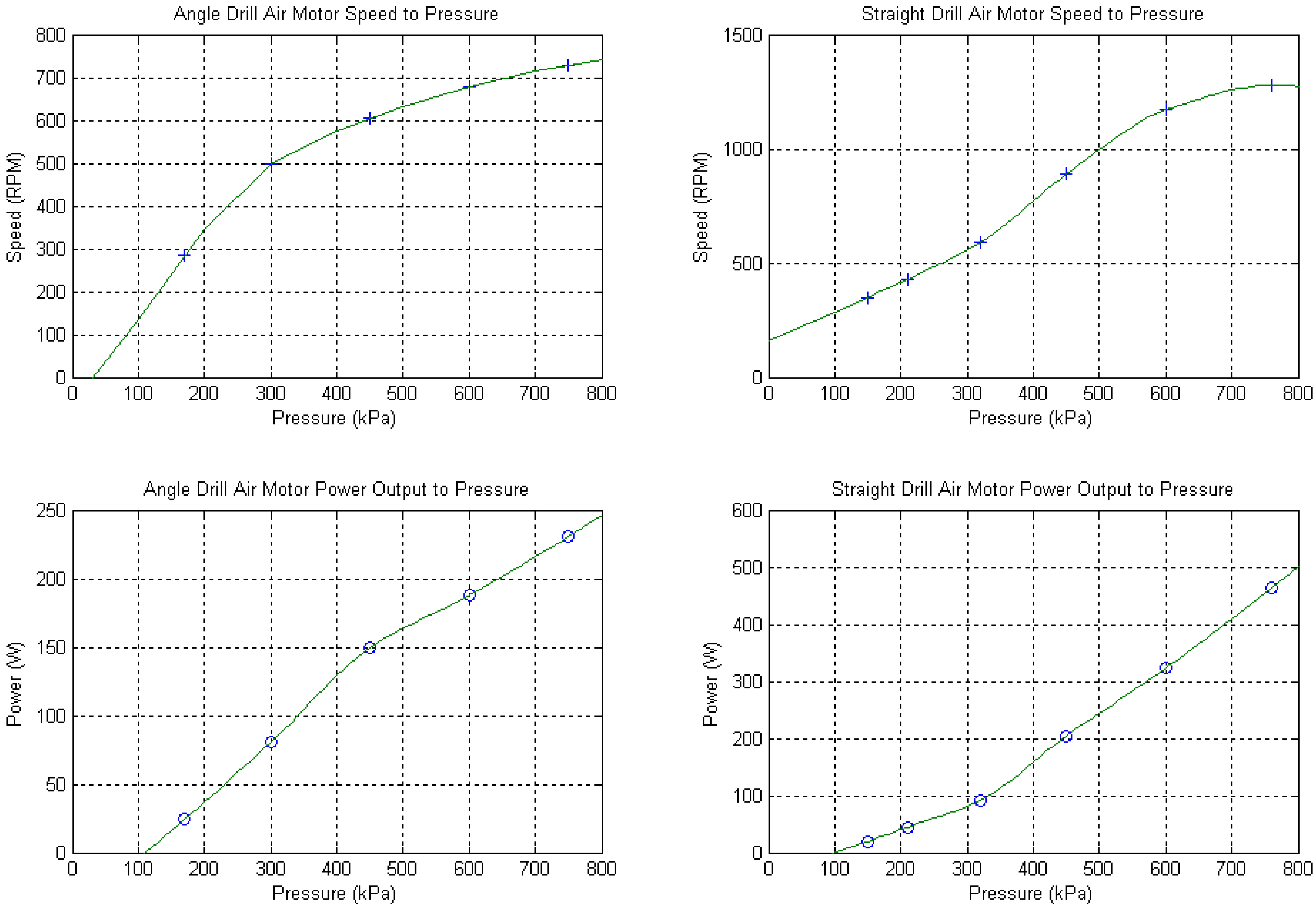


Figure 23 - Air Drills Performance Curve

Once the maximum efficiency profile was produced the total energy for the system could be found using Figure 24; power out over time curve. This represented the time each test lasted for at each of the pressures tested. The graphs output can give the amount of energy in kWhr due to the relationship power has to time.

Figure 24 show the combined total time which the maximum output power lasted for, this was 182 seconds for the angle drill and 132 seconds for the straight drill. This gave an efficiency of $8 - 10\,\%$ which was not a true representation of the system, as the air drills would not have lasted for this time in a continious test from a full to empty receiver.

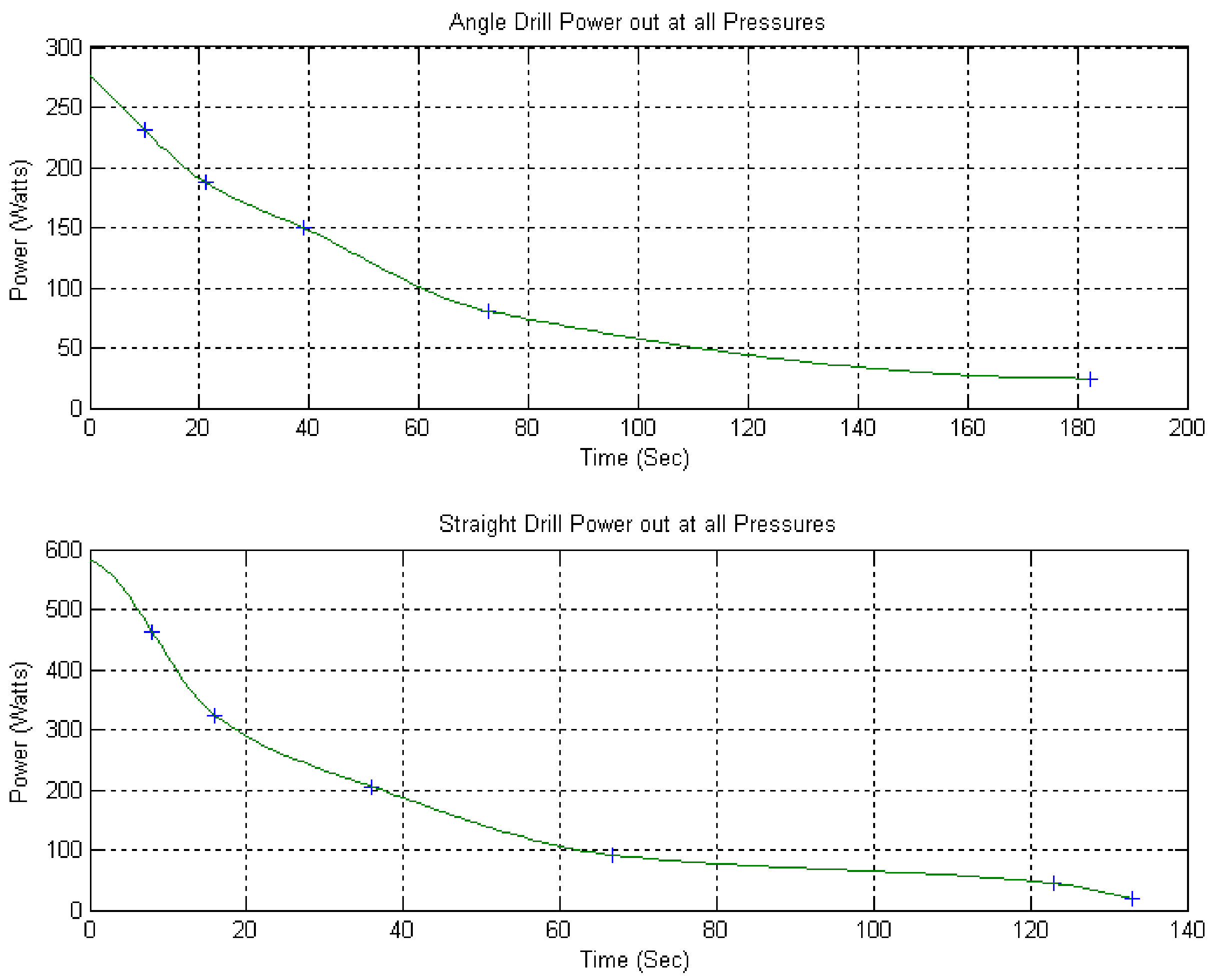


Figure 24 - Power Out Over Time

To find the true efficiences of the air drills some calculations had to be performed. This was done to find what proportion of the compressed air was used, in relation to the mass (kg) of the air in the receiver, using the ideal gas law. The results for both air tools can be seen in Appendix F. From the results it was found that the angle drills energy output was 1.92 Whr and 2.71 Whr for the straight drill.

The efficiency of the system is defined as the ratio of compressed air output to input power which was explained in Section 4.4. Using this ratio and knowing that the total input energy for the compressor was 54.5 Whr (Section 5.4) the efficiency of the air drill were calculated:

Angle drills efficiency:

$$\eta = \frac{0.00192}{0.0545} = 3.52\%$$

Straight drill efficiency:

$$\eta = \frac{0.00271}{0.0545} = 4.97\%$$

This shows that the efficiency of the system to be between $3 - 5\%$ which is due to all the losses in the system which were mentioned in Section 5.3.

To confirm that the system efficiencies were indeed correct a further test using the maximum efficiency profile was performed to find the actual performance of the drills. This was done using *Tank_Usage.m* script in Appendix I.

To perform this test the regulator was set at 750 kPa as this is where the maximum power output was achieved for both drills in Figure 23. With a full receiver and compressor switched off the air drills were run at their maximum efficiency. The results from this test can be seen below in Figure 25 and it can be noted that the straight drill lasted for 28 seconds and the angle drill 33 seconds.

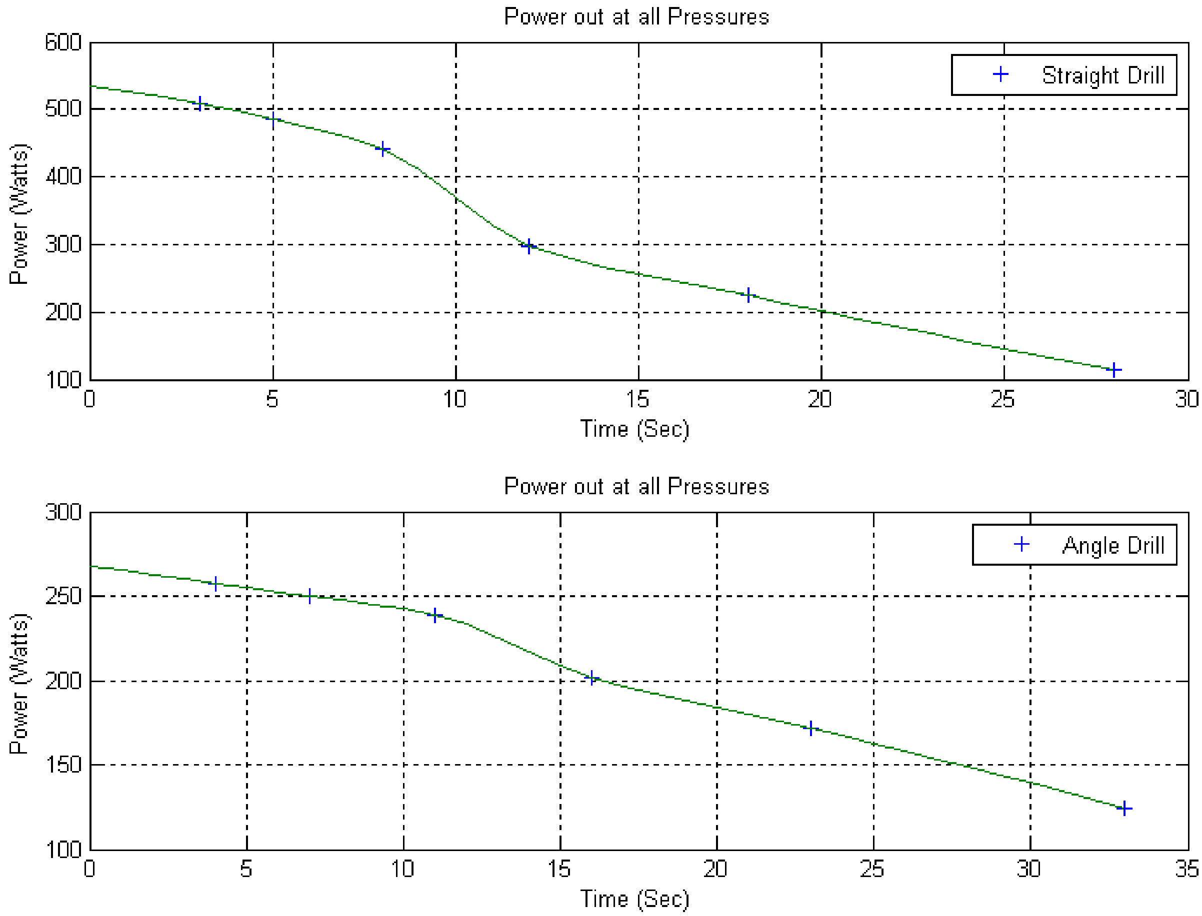


Figure 25 - Both Air Drill Best Efficiency Power Vs Time

Using Figure 25 and MATLABs® interpolation function, the kilowatt hours of each drill could be calculated. To find the are under the curve, MATLABs® step function `trapz()` was used with a step internal of one second. This would result in the answer being in kilowatts per second ($\frac{kW}{s}$) which is also the same as kilojoules (kJ).

To find the total energy of the system the following relationship was used:

$$\frac{kJ}{3600} = kWhr$$

This would give a total energy output of 1.8 Whr for the angle drill and 2.4 Whr for the straight drill.

The efficiency was then calculated using the energy from the air tools over the energy used by the compressor to fill the tank:

Angle drills efficiency:

$$\eta = \frac{0.0018}{0.0545} = 3.4\%$$

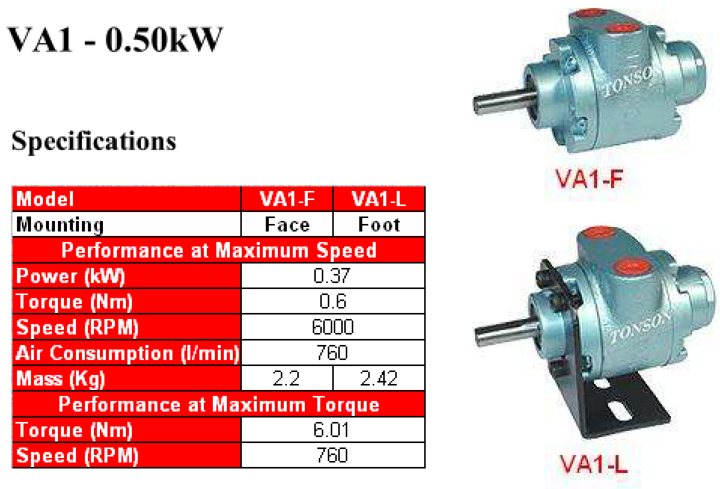
Straight Drill efficiency:

$$\eta = \frac{0.0024}{0.0545} = 4.5\%$$

The results from the maximum efficiency profile during this test now confirm that the efficiency of the system is only $3 - 5\%$.

Knowing the energy which the air drills outputted the power-to-weight ratio for the drills could also be calculated using the receiver volume of $65\ L$. It was found that the angle drills specific power was $28.5\ \frac{mWhr}{Liter}$ and straight drills specific power was $37\ \frac{mWhr}{Liter}$.

Therefore like it was stated earlier the results for the ideal equations were not able to be reproduce though practical testing. Where the ideal equation achieved an energy output of approx. $47\ Whr$ at 750 kPa in practice, the system was only able to achieve $2 - 3\ Whr$ of energy. If this system was able to output a continuous $47\ Whr$ at 750 kPa then using the compressor input energy $(54.5\ \text{Whr})$ we can work the efficiency out to be 87%. This wasn't the case; after all the testing was complete the efficiency was only $3 - 5\%$. To further compare results between the theory and practical the specific power of the system also was substantially higher for the ideal equation with $228 \frac{mWhr}{Litre}$ (adiabatic) and $419 \frac{mWhr}{Litre}$ (isothermal) whereas only approx. $37 \frac{mWhr}{Litre}$ was achieved from practical testing.



Model	VA1-F	VA1-L
Mounting	Face	Foot
Performance at Maximum Speed		
Power (kW)	0.37	
Torque (Nm)	0.6	
Speed (RPM)	6000	
Air Consumption (l/min)	760	
Mass (Kg)	2.2	2.42
Performance at Maximum Torque		
Torque (Nm)	6.01	
Speed (RPM)	760	

Figure 26 - Air Motor Specification (Ltd., 2006)

It must be noted that the results after testing the air motor did not compare to actual real life data for air motor designed for this application. Figure 26 shows the details of a $370\ W$ air motor which uses $760\frac{L}{min}$ and the performance at maximum torque is $6\ Nm$ at $760\ RPM$. The straight drills maximum performance was $460\ W$ for 8 second and for this to be achieved it used approx. $112\frac{L}{min}$. The performance at maximum torque was $3.5\ Nm$ at $1280\ RPM$. If a larger tank were used and a compressor that could keep up with demand then this result could have been better. This information confirms that if an air motor of this type was as a replacement for the air drill, then a lot more stored air would be needed for this to operate correctly and for the required amount of time.

5.7. Comparison Between Storage Devices

In Section 4.2 it explained the desired characteristics of a storage device which we will look at now to give some comparison between the findings from the theoretical analysis and the dyno testing. It was found from the results that the characteristics for this SCAES system where.

- Long cycle life
- Robustness.

- Simple to maintain.
- Low environmental impact
- Quick recharge capacity for size of receiver

Comparing this to batteries using the specific power of the system, Figure 27 shows five common batteries used every day. It is evident from the graph that all batteries have higher Specific Power than that of theoretical isothermal and adiabatic ideal equations (Figure 20) and the specific power obtained though dyno testing. From Figure 27 the lowest specific power was for lead acid battery at 70 $\frac{Whr}{Liter}$ highest Lithium-ion and Alkaline at 400 $\frac{Whr}{Liter}$.

Although the values in Figure 20 are low these would improve if the pressure and receiver volume were increased but this then would have its own safety risks and larger footprint compared to any of the batteries footprint mentioned below in Figure 27.

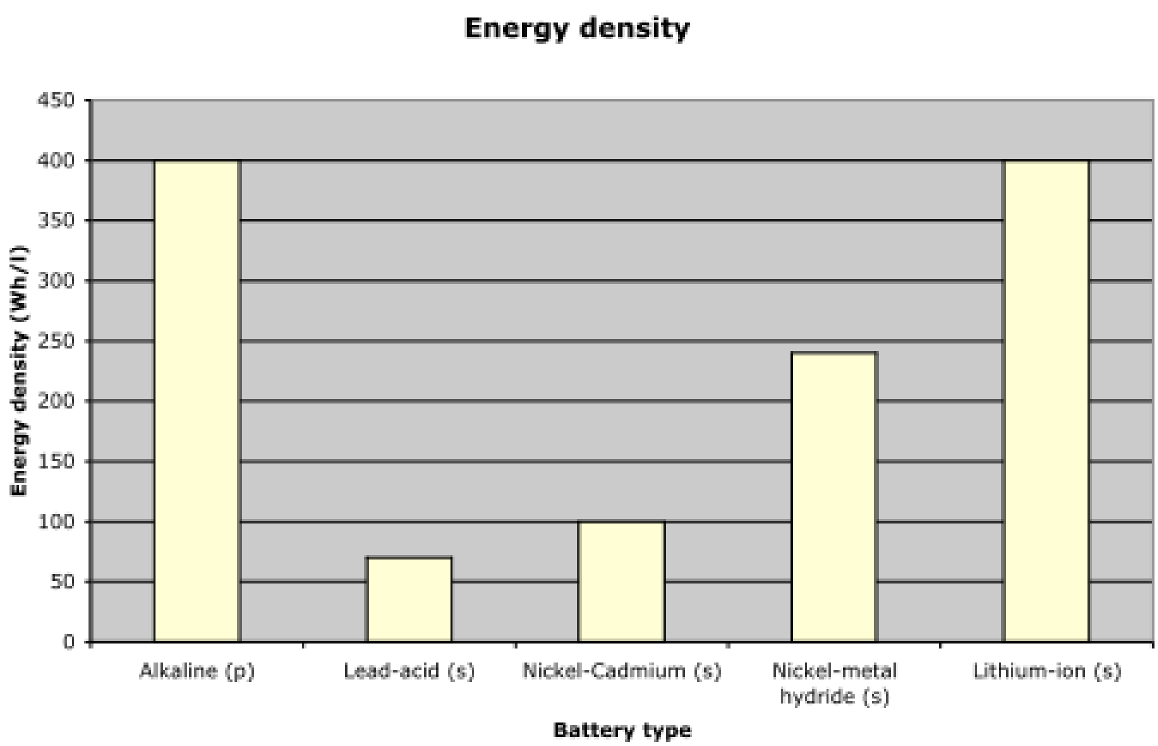


Figure 27 - Energy Density for Various Batteries (Reddy, 2010)

Looking at the characteristics of batteries and comparing them to the above mentioned characteristic for the SCAES system. Batteries would have the following,

- High energy to weight ratio.
- High battery capacity.
- Long cycle life.
- Relative Low cost.
- Fast response.
- Current fluctuation tolerance.
- Low self-discharge rate.
- High cell or battery voltage.
- High turn-around efficiency.
- High depth of discharge.

If we look at the SCAES system alone, it took 120 seconds for the compressor to fill the $65\ L$ receiver and from that stored energy the air motors were able to produce $2 - 3\ Whr$ for a period of between $28 - 33$ seconds.

Now for the same output, if a 9 Volt battery was to output $4.8\ V$ at $500\ mA$ an hour this has the capacity to supply $2.4\ Whr$. This storage device unlike SCAES is ready to supply power as soon as it is purchased, and is able to fit in the palm of your hand (Appendix H). Depending on the type and brand of the battery it could cost between \$8.00 – \$20.00.

5.8. Estimation on Size of Receiver for SCAES

Using the data collected in the dyno test and linear scaling, it was estimated that a $65\,000\ L$ receiver with dimensions of that in Figure 28 would be needed to store $3\ kWhr$ of energy. This amount of stored energy will not be enough to supply an average household for one day as the average consumption of energy is between $20 - 30\ kWhr$. If this amount of energy was to be storage then the receiver would have to be $650\,000\ L$ which is equivalent to a 25-metre swimming pool.

When considering this as a storage method, considerations need to be made on the safety aspects of the system as the stored pressure could potentially have the effects of a bomb. Certification for the receiver and relief values and restraining devices for pipework would all need to be current and checked on a regular basis as if the receiver did fail the consequence could be very high. In addition to this the size would not be a feasible option due the area and size it would occupy in a yard.

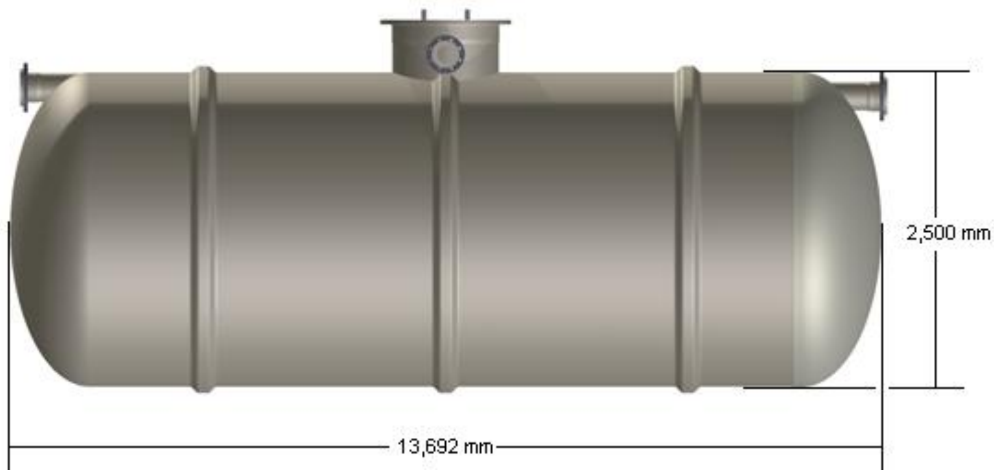


Figure 28 - Size of Storage Receiver to Hold 3 kWhr

5.9. Cost

The cost of the SCAES system used in the dyno test would be approx. $\$800.00$ to buy new. Where a new compressor would total $\$600.00$ and air tool $\$200.00$. When considering the receiver to hold 3 $kWhrs$ of energy the receiver alone would cost approx. $15,000 then on top of this the cost of the compressor, air tools, piping, safety reliefs, certification, good foundations, control system and labor which could add an extra $\$10,000$. Therefore the total cost for an initial outlay would be approx. $\$25,000$. This may seem expensive but the life cycle for SCAES could be $30 +$ years with ongoing maintenance.

If this air compressors motor ($1.5\ kW$) was to be powered by solar panels, to fill the $65\ 000L$ receiver it would take approx. 30 hours. In saying this if this system was assembled a recommendation would to have multiple compressors and larger compressors to supply more air to fill the receiver quicker. If a 3 kW solar system was used of 12 x high efficiency 250 W solar panels and a 3 kW solar inverter. The output of this would be 10 $kWhr$ per day working on 5 peak sun hours (PSH) a day for 6 days. The cost of this system would be approx. $\$6000$ which would bring the total SCAES system to approx. $\$31,000$.

A battery system on the other hand of the same storage capacity would initially have a smaller initial cost but could over the space of $30+$ years end up costing more. A true deep cycle gel-cell valve regulated lead acid battery can be expensive but should have a discharge capacity of up to 80%. But no matter how good the battery is if you want it to last and not pack up after a few months of use, it is generally accepted that you should never discharge a battery by more than 30% of its capacity (Kier, 2009).

Using the steps in Appendix G it was found that $5\ x\ 12\ V$ batteries with a capacity of $200\ Ah$ would be required to store $3\ kWhrs$ if the depth of discharge was 30%. In saying this, the cost per batteries would be approx. $\$550$ totaling $\$2800$, and then you would need an inverter, a charging system and regular planned maintenance which could add another $\$5000$.

These types of batteries typically have a maximum life of three years which would mean over the life cycle of the CAES system they would be replaced 10 times. Therefore this system could cost approx. $\$33{,}000$ over 30 years. But the advantage batteries have is they are ready to supply power from the moment they are installed.

CHAPTER 6

6. DISCUSSION

6.1. Introduction

The work done during this research was to validate whether SCAES (using off the shelf equipment) could offer a viable alternative solution to energy storage requirements in a house hold situation. SCAES technology would dramatically lighten the loads on electricity networks and serve as an advantage to those people living in developing countries, or cannot connect to a power grid. In addition to this the heat energy from compression could be captured and used for heating our homes, for hot water, cooking or even generating electricity.

6.2. The Efficiency of a Compressed Air System

The overall efficiency of a compressed air system can be as low as $10 - 15\%$. (Moskowitz, 2010). When considering the efficiency of the system all the possible losses must be taken into consideration which may occur from the moment a certain quantity of air enters the compressor until it is exhausted from the air motor.

These losses are chargeable:

1. To air being taken into the compressor if it is being supplied from a hotter place. This results in a lesser quantity (weight) of air being taken into the cylinder per stroke, thereby increasing the power required to compress a given quantity of air per unit of time. This loss can be prevented by making adequate provisions for the air in-take from the coolest outside place around the compressor building.
2. To friction in the compressor. This will amount ordinarily to a power loss of from $15 - 20\%$. It can be reduced by good workmanship to about 10%, but cannot be avoided altogether.

3. To a series of imperfections in the compressing cylinders, such as insufficient supply of free air, difficult discharge, defective cooling arrangements, poor lubrication, etc.
4. To heat generated during compression which increases the power required for compressing a given quantity of air, for which there is no return, as the heat is afterward dissipated in transmission.
5. To loss of pressure in the pipe line, due to friction, etc.
6. To friction and fall of temperature during expansion of the air in the cylinder of the air engine.
7. To leaks in the compressor, the pipe line, and in the air engine (Simons, 1914).

From the literature review on the Huntorf and McIntosh plants it is said that the cycle efficiency of the systems are 60% and 75% respectively. But theses efficiencies are based on the assumption $1\ kWhr$ of gas used in a combined cycle gas turbine has a realistic efficiency of 55%. When looking at the input energy and using the total electricity plus the total gas the efficiencies drop to 42% and 54% respectively. These efficiencies are reasonable considering that these are sophisticated plants with the McIntosh plant costing 65 million dollars (Energy C. , 2012).

The low efficiency which was calculated from the dyno testing of $3 - 5\%$, even though is quite poor could be improved with the use of new equipment or a change in design. It must be mentioned that all the equipment used in the practical dyno test had already been in service for many years.

The compressor was made 30 years ago and over this time has had little to no maintenance to any internal components of the compressor. If a new compressor was used then the input energy could be lower which in-turn would improve overall efficiency.

In addition to this the air tools used had four rotor blades (Appendix E) which with use over the year could have excessive wear. Vane type air tools can have from three to ten vanes and by increasing the number of vanes reduces internal leakage or blow by. This would make the output torque more uniform and reliable at lower speeds. However more vanes increase the friction, cost of the motor and decreases efficiency (Air Motors, 2012).

Air tools are not designed with this application in mind, and if correct air motors were used the then overall efficiency of the system could have been higher.

The air drills did perform as the theory suggests with maximum power achieved when the air motor was operating at about half its free speed, this is where they are most efficient (Air Motors, 2012). In addition to this the maximum power output for the straight drill could be confirmed from the specification in Appendix E.

For further comparison, the modern gasoline engine efficiencies have a maximum thermal efficiency of about $25\% - 30\%$ when used to power a car. In other words, even when the engine is operating at its point of maximum thermal efficiency, the total heat energy released by the gasoline consumed is about $70 - 75\%$.

Approximately half of this rejected heat is carried away by the exhaust gases, and half passes through the cylinder walls or cylinder head into the engine cooling system. This is passed to the atmosphere via the cooling system radiator. Some of the work generated is also lost as friction, noise, air turbulence, and work used to turn engine equipment and appliances such as water and oil pumps and the alternator, leaving only about $25 - 30\%$ of the energy released by the fuel consumed available to move the vehicle (Physics).

Although the practical results were substantially lower than that of the theory the result for the dyno testing were confirmed two different ways which suggest that the efficiencies for this system were correct.

As the main inefficiencies are due to heat of compression if this heat was able to be captured and reused either when the air leaves the receiver then this would add more energy to the compressed air. In addition to this if the heat was captured and used in other areas like heating our homes or hot water, for cooking or even generating electricity then from this one renewable resource it can have multiple uses.

6.3. **Other Alternatives**

In the project specification for this dissertation one of the outcomes was to investigate other alternatives for a the primary energy source or direct drive of the compressor, like using wind turbine, solar thermal etc.

In the literature it was found that there was research conducted on using renewable energies for the primary energy for CAES system which are known as Hybrid CAES (HCAES).

The traditional way of utilizing wind energy is for a turbine to drive a generator and produce electricity which in turn would power an air compressor. When considering a direct drive compressor using a wind turbine the air compressor and turbine need to be matched so that they operate at the same speed range for all wind conditions which would be more involved than generating electricity to power the air compressor. This also raises a point that if the wind turbine was producing electricity then multiple compressors could be run whereas direct coupled on one compressor could be used.

Another option would be to use hydraulics, which would be much more efficient then air but does come with its own problems. Like the close fitting components in the pump which causes much friction and requires a lot of force to turn the motor, or having the oil at the right temperature. If the oil is cold this would increase the viscosity creating more friction. The last consideration would be to the size of receiver required to store a reasonable amount of energy.

There is very limited information regarding solar thermal energy and compressed air. The literature did reveal though that solar air-conditioning is considered as a thermal storage unit. But it uses the thermal energy to preheat the refrigerant before it is directly feed into the compressor. If this was to be considered to direct drive a compressor the energy would need to be converted into form i.e. electricity, before it can be utilized to power a compressor. With this conversion there would inherently be some losses.

When considering a pumped storage hydro as an energy system there are three main factors that determine the generating potential at any specific site: the amount of water flow per time unit, the vertical height that water can be made to fall (head) and the body of water used as storage.

Unlike wind and solar which are abundant in times of drought the volume of water storage will decrease and evaporate leaving no water to use for energy to power the compressor. Like wind turbines pumped storage hydro systems are typically connected to generators producing electricity on demand to run equipment like air compressors.

With any of these other alternatives there is still an issue with the storage of compressed air and the size of receiver required to store the amount of energy needed. This was very evident with the SCAES system on which this dissertation is based. By using these other alternative energy source this is not going to change the size of receiver but could improve the efficiency of the system. More research would be required to investigate how these alternatives would behave if the SCAES systems pressure was raised above $1000\ kPa$, as with higher pressures the specific power and energy from the compressed air is much greater and more air can compressed into a receiver.

CHAPTER 7

7. CONCLUSION

7.1. Introduction

The initial basis of this research was the assumption that compressed air could offer an alternative to commercial energy storage technologies for house hold use. The focus was on off the shelf products that could be combined in order to deliver the required energy storage and delivery method. The overall efficiency of the SCAES system was very low and with further research it would be possible to increase efficiencies of SCAES by improving

- Compression and decompression by using more effective isothermal processes
- Adding intermediate air receivers between pressures to increase the usable storage time and helping more effective heat transfer to take place.
- Increasing the pressure above $1000\ kPa$ with larger compressor
- Replacing air tool with air motors designed for this application
- Recapturing the waste heat and using it in other areas
- Heating the air on output of receiver to add more energy back into the compressed air

7.2. Achievement of Project Objectives

Research the background information on renewable energies and in particular CAES

The results of this research are outlined in Chapters 2 and 3. The background literature has provided results that there are CAES plants which are currently operating throughout the world. This technology is an effective solution for compressed air energy storage to help alleviate the demand on the electricity network.

Design a CAES as a storage and regeneration plant for a domestic household using off-the-shelf componentry

The SCAES system proposed in this dissertation used off the shelf equipment to a maximum pressure of $1000\ kPa$. Chapter 4 and 5 explains this equipment and how it is used within the system.

Identify all alternatives for the primary energy generation system. PV, wind, solar thermal and used for direct compression

In Chapter 6 the other alternatives was discussed and from the finding within this report found that looking into these alternatives would not help the fact that, the size of the receiver in this system governs the amount of energy that can be stored. So at $1000\ kPa$ it does not matter how the air is compressed it is how it is stored which should be investigated further for a small system.

Identify efficiency of energy transfer of the system

Chapter 5 gives the results for the proposed SCAES system from a dyno test using off the shelf equipment. A discussion about the efficiency of the system can be found in Chapter 6 which compares compressed air efficiency to other equipment.

Identify cost effective componentry that matches the system requirements

The cost of the off the shelf equipment was provided in Chapter 5 in addition to this an estimation cost comparison was made between a large SCAES system and a battery system or equivalent size.

Create a computational model to assist in system design and optimization

MATLAB® was used to create a model of the ideal thermodynamic equations and a model of the data gathered during the dyno testing. These scripts can be found in Appendix I.

Use the model to analyse the potential for CAES to be employed as a cost effective functional alternative energy storage and regeneration system for domestic households

Estimations of the size of SCAES system were done using linear scaling in MATLAB® using the data gathered in the dyno testing. The results of this can be found in Chapter 5.

Implement the CAES design using off-the-shelf componentry into a domestic household application to confirm design and results

A practical dyno test was performed to test the performance of the compressor and air motor. Details of the equipment can be found in Chapter 4 and the results of testing in Chapter 5.

7.3. Change of Design

The idea behind this dissertation was storage of compressed air energy for use with electrical items within your home like air conditioning, which is a large consumer of energy.

With air conditioning in mind further work that could be undertaken would be to investigate direct solar air conditioning or using an ejector for the refrigeration process.

Direct solar air conditioning could be considered as a thermal storage unit. The process collects solar energy though a thermal collector to preheat the refrigerant before it's directly fed into the compressor. The design of the system reduces the amount of work needed to be done by the compressor therefore it can be smaller which also helps reduce electricity costs. The systems are designed to operate at ambient temperature but the more heat the collector is exposed to, the greater the efficiency.

The Ejector cycle is a promising cycle for the utilization of solar energy for cooling; its greatest advantage is its ability to produce refrigeration using waste heat or solar energy as a heat source at temperatures above $80°C$. The ejector is used instead of a conventional expansion valve to expand high-pressure refrigerant by using energy which previously was lost. A gas-liquid separator separates expanded refrigerant into gas and liquid so that gas refrigerant is directly drawn into the compressor at a higher pressure while liquid refrigerant flows into the evaporator to exchange heat with air.

This means that the compressor power consumption can be reduced and you can get high evaporator performance as only liquid refrigerant flows into the evaporator, reducing pressure loss and improving evaporator performance.

7.4. **Future Work and Improvements**

Having completed a base line with SCAES using only $1000kPa$ and $0.065m^3$ receiver, there are many improvements which could now be incorporated to improve the results obtained by testing and raise the efficiency of the system.

Some of these improvements would be

1. Investigate the possibility of increase the pressure to $5000 - 7000\ kPa$ like that of Hundorf and McIntosh CAES plants to see if this would be better suited to SCAES for house hold use. Also in performing tests at higher pressures further increase the pressure to $200 - 300\ MPa$ as it is said in Ulf Bossel paper under ideal reversible isothermal conditions a $300\ L$ tank at $20°C$ filled to $300\ Bar$ of compressed air carries $51\ MJ$ of energy (Bossel, 2009).

2. The air drill used for this SCAES system were designed to be used on a work site. These tools are not designed with system efficiencies in mind. Air motors on the other hand are especially designed for this purpose and for this reason replacing air tools with air motors would see the efficiency of the system increase.

3. Instead of using an air motor investigate the system performances when using an air nozzles / knife forcing a tesla turbine. The nozzle uses the coanda effect or small directed nozzles to amplify compressed airflow up to 25 times more (Australia C. A., 2013). The airstream that results is a high volume, high velocity blast of air at minimal consumption.

4. Investigate the effects of reheating the compressed air, this will increase the efficiency and makes it possible to use a smaller air compressor for performing a given amount of work. In addition to increasing the efficiency, the reheating of compressed air also prevents the freezing of the exhaust ports of air engines which often becomes troublesome when air containing considerable moisture is exhausted at temperatures below the freezing point (Simons, 1914).

Bibliography

1. *Air Motors*. (2012, 1 1). Retrieved 7 4, 2013, from Hydraulics and Pneumatics: http://hydraulicspneumatics.com/200/TechZone/FluidPowerAcces/Article/False/6422/TechZone-FluidPowerAcces

2. Association, E. S. (2011). *Electricity Storage Association*. Retrieved 4 16, 2013, from Technology Comparision: http://www.electricitystorage.org/technology/tech_archive/technology_comparisons

3. Australia, C. A. (2013). *Air Nozzle Selection Guide*. Retrieved 10 10, 2013, from Compressed Air Australia: http://www.caasafety.com.au/air-nozzles-jets/air-nozzles

4. Australia, G. (2011, 11 11). *Geoscience Australia*. Retrieved 5 1, 2013, from Energy: http://www.ga.gov.au/energy/australian-energy-resource-assessment.html#

5. Bossel, U. (2009). *Thermodynamic Analysis of Compressed Air Vehicle Propulsion.* Switzerland .

6. Challenge, C. A. (2003). *Improving Compressed Air System Performance.* Washington, DC: Lawrence Berkeley National Laboratory.

7. Connolly, D. (2010, 10 11). A review of energy storage technologies for the integration of fluctuating renewable energy. Limerick, Limerick, Ireland: University of Limerick .

8. Consulting, M. H. (2012). *Energy Storage in Australia.* Brisbane: Marchment Hill Consulting .

9. Cunha, I. F. (2012 , 12 18). *Sustainability Victoria.* Retrieved 8 23, 2013, from Sustainability Victoria: www.sustainability.vic.gov.au/.../best_practice_guide_compressed_air.pdf

10. Das, T., & McCalley, J. D. (2012). *Compressed Air Energy Storage.* Iowa : Iowa State University .

11. Energex. (n.d.). *Saving energy during peak times*. Retrieved 7 24, 2013, from Energex Positve Energy: http://www.energex.com.au/residential-and-business/peak-demand

12. Energy, C. (2012). *Huntorf Compressed Air Energy Storage Facility*. Retrieved 2 2, 2013, from Clean Energy Action Project: http://www.cleanenergyactionproject.com/CleanEnergyActionProject/Energy_Storage_Case_Studies.html

13. Energy, C. (2012). *MacIntosh Compressed Air Energy Storage Plant*. Retrieved 2 2, 2013, from Clean Energy Action Projet: http://www.cleanenergyactionproject.com/CleanEnergyActionProject/Energy_Storage_Case_Studies.html

14. H Paloheimo, M. O. (2009). A Feasibility Study on Compressed Air Energy Storage System for Portable Electrical and Electronic Devices. *Clean Electrical Power*, 355 - 362.

15. Harrison, P. J. (n.d.). *Michigan State University* . Retrieved 4 14, 2013, from Department of Chemistry: http://www.chemistry.msu.edu/

16. Hepworth, A. (2011). *Rooftop solar panels overloading electricity grid* . Sydney: The Australian.

17. Institute, S. S.-m. (2010). *Analysis of compressed air storage* . Lithuania: Strategic Self-management Institute.

18. International, F. D. (2010). *Australia's Energy Future - A Time for Reflection.* Perth: Future Directions International.

19. J.R.Jenneson. (1998). *Electrical principles for the Electrical Trades.* Roseville, NSW: McGraw-Hill Book Company.

20. Khamis, A., Badarudin, Z., Ahmad, A., Rahman, A., & Hairi, M. H. (2010). *Overview of Mini Scale Compressed Air Energy Storage System.* Malaysia: The 4th International power engineering and Optimization confronce.

21. Khamis, A., Badarudin, Z., Ahmad, A., Rahman, A., & Hairi, M. H. (2011). *Development of Mini Scale Compressed Air Energy Storage System.* Malaysia: University of Malaysia.

22. Kier. (2009, 9 27). *Battery Calculations*. Retrieved 10 1, 2013, from Street Musician: http://www.streetmusician.co.uk/batterycalculation/

23. Klenck, T. (1997, 5 1). *How It Works: Air Compressor*. Retrieved 8 30, 2013, from Popular Mechanics : http://www.popularmechanics.com/home/improvement/energy-efficient/1275131

24. Ltd., T. A. (2006). *Vane Air Motors.* Retrieved 10 16, 2013, from Specialised Air Motors and Transmission: http://www.samt.com.au/vane-air-motors/va1-050kw.html

25. Matters, E. (2012, 12 5). *Renewable Energy News*. Retrieved 02 10, 2013, from Solar Power Australia 2011-12 Report Highlights: http://www.energymatters.com.au/index.php?main_page=news_article&article_id=3498

26. Moskowitz, F. (2010). *Heat Recovery and Compressed Air Systems.* Arizona : Compressed Air Challenge .

27. Paloheimo, H., & Omidiora, M. (2009). A Feasibility Study on Compressed Air Energy Storage System for Portable Electrical and Electronic Devices. *2009 International Conference on Clean Electrical Power,* , 355 - 362 .

28. Pauken, M. (2011). *Thermodynamics for dummies.* Indiana: Wiley Publishing Inc.

29. Physics, E. (n.d.). *Efficiency of a Carnot engine*. Retrieved 8 1, 2013, from Essential Physics: http://www.essential-physics.com/samples/BookInd-1600.html

30. Primm, A. J. (2011). *Analysis of Flexible Fabris Structures.* University of Nottingham.

31. R.K.Rajput. (2007). *Engineering Thermodynamics 3rd Edition.* Delhi: Laxmi Publication LTD.

32. Reddy, T. (2010). *Linden's Handbook of Batteries, 4th Edition.* McGraw-Hill Professional.

33. Simons, T. (1914). *Compressed Air.* LONDON: McGRAW-HILL BOOK COMPANY,.

34. Statistics, A. B. (2013, 03 28). *2011 Census Quickstats*. Retrieved 03 28, 2013, from Census for a brighter future: http://www.censusdata.abs.gov.au/census_services/getproduct/census/2011/quickstat/0

35. Tas Luttrell. (2010). *Australia's Energy Future: A time for Reflection.* Perth: Future Directions International.

36. Taylor, J., & Halnes, A. (2010). Analysis of Compressed Air Energy Storage. *PCIC Europe 2010 Conference Record* , (pp. 1-5). Oslo.

37. Toolbox, E. (n.d.). *Types of Air Compressors*. Retrieved 09 08, 2013, from Engineering Toolbox: http://www.engineeringtoolbox.com/air-compressor-types-d_441.html

38. Vadasz, P. (2009). Energy Storage Systems. In Y. Gogus, *Encyclopida of life support systems* (p. Vol 1). Durban, South Africa: Encyclopida of Life Support systems Publishers Co Ltd.

39. Vongmanee, V. (2009). The Renewable Energy Applications for Uninterruptible Power Supply Based on Compressed Air Energy Storage System. *2009 IEEE Symposium on Industrial Electronics and Applications (ISIEA 2009).* Kuala Lumpur, Malaysia.

40. Willis, H. L., & Scott, W. G. (2000). *Distributed Power Generation : Planning and.* CRC Press.

41. Yunus Cengel, M. B. (2002). *Thermodynamics and Engineering Approach.* Boston: Mcgraw-Hill College.

Appendix A – Project Specification

University of Southern Queensland

Faculty of Health, Engineering & Sciences

ENG 4111 / 4112 Research Project

PROJECT SPECIFICATION

For: Kayne HERRIMAN (0050051064)

Topic : Compressed Air Energy Storage System for residential use.

Supervisors: Dr Leslie Bowtell

Co-Supervisor: Dr Ray Malpress

Sponsorship: Own Project

Project Aim: To investigate the possibility of using a Compressed Air Energy System (CAES) in a domestic household application i.e. Air Conditioning, to reduce the peak electrical demand.

Program:

1. Research the background information on renewable energies and in particular CAES.
2. Design a CAES as a storage and regeneration plant for a domestic household using off-the-shelf componentry.
3. Identify all alternatives for the primary energy generation system. PV, wind, solar thermal etc.
4. Investigate direct air compression from the primary energy source, e.g. wind turbine driven compressor.
5. Identify efficiency of energy transfer of the various options

6. Identify cost effective componentry that matches the system requirements
7. Create a computational model to assist in system design and optimization
8. Use the model to analyse the potential for CAES to be employed as a cost effective functional alternative energy storage and regeneration system for domestic households.

As time and resources permit:

1. Implement the CAES design using off-the-shelf componentry into a domestic household application to confirm design and results

Agreed:

Student Name: Kayne Herriman

Date: 30/03/2013

Supervisor Name: Dr Leslie Bowtell / Dr Ray Malpress

Date:

Examiner/Co-Examiner:

Date:

Appendix B – Extended Abstract

Small Compressed Air Energy Storage (SCAES)

Sponsor – Own Project

Kayne Herriman

Electrical / Electronic Engineering

Supervisors: Dr Leslie Bowtell, USQ

Dr Ray Malpress, USQ,

Keywords: ***SCAES, Energy, Storage***

Introduction

Australia is seen to be blessed with abundant renewable energy resources and it has been said that Australia is the 'Middle East' of renewables. These "free" resources substantially exceed Australia's total energy demand, both currently and into the foreseeable future.

Compressed Air Energy Storage (CAES) systems uses stored compressed air as an energy source, to create power on demand by releasing the energy to turn a turbine. The proposed design uses solar energy as the input source so that no dependence is placed on mains power. (Figure 1)

Compressed Air Energy Storage

CAES technology is not unproven; on a large scale there are two existing CAES plants which are operational. One in Huntorf, Germany (321MW for two hours, built in 1978), and the other in McIntosh, Alabama, USA (190MW for 26 hours built in 1991)

Small CAES (SCAES) technology would dramatically lighten the loads on electricity networks, serve as advantage to those people living in developing countries, or cannot connect to a power grid.

Methodology

CAES systems compress air adiabatically or isothermally, as these equations are 'ideal' the results are never actually achieved by physical machines. Adiabatic is a process occurring without exchange of heat of a system with its environment and Isothermal is a change of a system, in which the temperature remains constant.

Theoretical analyses of these processes were done to calculate the amount of energy that would be returned, which was compared to data gathered from bench testing an air drill as a dynamometer.

Results

From the correlation between theoretical analysis and data produced from the dynamometer the following outcomes could be achieved

- 'Ideal' systems energy output
- Efficiency of the CAES system
- The size of receiver required to store desired amount of energy.

Further Work

Test SCAES to 20 MPa for comparison between the projects.

Test using an air motor of equivalent size in place of air drill to try and achieve better efficiency

Conclusions

SCAES systems at low pressures (1000 kPa) are not a feasible option as energy source. The size of storage receiver required compared to that of batteries of the same output power the footprint is considerably smaller.

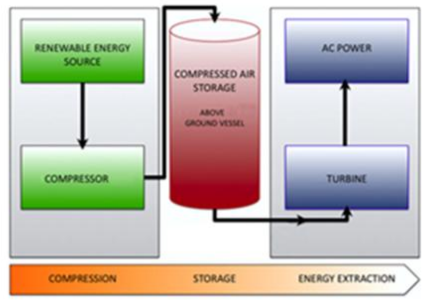


Figure 1 - Design of SCAES system

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I would like to thank my supervisors Dr Leslie Bowtell and Dr Ray Malpress. Their willingness to share their vast technical knowledge and give simple explanations made this dissertation easier to complete. I appreciated all the time and effort you gave throughout the year.

References

Yunus Cengel, M. B. (2002). *Thermodynamics and Engineering Approach.* Boston: Mcgraw-Hill College.

Khamis, A., Badarudin, Z., Ahmad, A., Rahman, A., & Hairi, M. H. (2010). *Overview of Mini Scale Compressed Air Energy Storage System*. Malaysia:

Appendix C – Ideal Thermodynamics Calculations

Isothermal Compressed Air Energy Storage

Variables

- Compressed air pressure = 1000 kPa
- Temperature in K = 20 +273 = 293 K

Free energy in this case is given by:

$$W = RT\left[ln\frac{P_f}{P_i}\right]$$

Where

- W = Energy in Joules/kg
- Pf = final in kPa
- Pi = initial in kPa
- R = gas constant (0.287 kJ/kg.K)
- T = absolute temperature 273K

Energy (W) is given by:

$$W = 0.287\frac{kJ}{kg.K} * 293\text{ K}\left[ln\frac{1000\ kPa}{100\ kPa}\right] \Rightarrow 193.6\ \frac{kJ}{kg} \Rightarrow \frac{193.6\ \frac{kJ}{kg}}{3600\ kJ} = 0.054\ \frac{kWhrs}{kg}$$

Volumetric energy density using the ideal gas law:

$$\frac{V}{kg} = \frac{RT}{P}$$

$$\frac{V}{kg} = \frac{287\frac{J}{kg.K} * 303\text{ K}}{1000\text{ kPa}} \Rightarrow 0.0840\ \frac{m^3}{kg} = \ 84\ \frac{Litres}{kg}$$

Energy density:

$$Density = \frac{W}{V} \Rightarrow \frac{54\ \frac{Whrs}{kg}}{84\ \frac{Litres}{kg}} \Rightarrow 0.64\ \frac{Whrs}{Litre}$$

Adiabatic Compressed Air Energy Storage

Variables

- Compressed air pressure = 1000 kPa
- Initial Volume = 0.065 m^3 / 65 Litre

Free energy in this case is given by:

$$W(kJ) = \frac{P_f(kPa) \times V_f(m^3) - P_i(kPa) \times V_i(m^3)}{\gamma - 1}$$

Where

- W = Energy in Joules
- Pf = final in kPa
- Pi = initial in kPa
- Vi = volume
- γ = Specific Gas Constant, 1.4

To calculate Mass in Kg

$$m\ (kg) = \frac{P_i(kPa) \times V_i(m^3)}{R(\frac{kJ}{kg.K}) \times T_i(K)}$$

$$m\ (kg) = \frac{100\ \text{k}Pa \times 0.065\ m^3}{0.287 \frac{kJ}{kg.K} \times 293\ K} = 0.0077\ \text{kg}$$

Temperature (Tf) given by

$$T_f(K) = T_i(K)\left[\left(\frac{P_f(kPa)}{P_i\,(kPa)}\right)^{(k-1)/k}\right]$$

$$T_f(K) = 293\ K\left[\left(\frac{1000\ kPa}{100\ kPa}\right)^{(1.4-1)/1.4}\right] = 565\ K$$

To calculate Volume final (Vf)

$$V_f(m^3) = \frac{m(kg) \times R\left(\frac{kJ}{kg.K}\right) \times T_f(K)}{P_f(kPa)}$$

$$V_f(m^3) = \frac{0.0077\ \text{kg} \times 0.287\frac{kJ}{kg.K} \times 565\ K}{1000\ \text{k}Pa} = 0.00125\ m^3$$

Free energy in this case is given by:

$$W(kJ) = \frac{P_f(kPa) \times V_f(m^3) - P_i(kPa) \times V_i(m^3)}{\gamma - 1}$$

$$W(kJ) = \frac{1000\ \text{k}Pa \times 0.00012\ \ m^3 - 100\ \text{k}Pa\ \times 0.065\ m^3}{1.4 - 1} = 1.5124kJ \Rightarrow \frac{1.5124\ kJ}{3600\ kJ} =$$

$$=\ 0.000420\ kWhrs$$

$$=\ \frac{0.000420\ kWhrs}{0.0077\ \text{kg}} = 0.0543\frac{kWhrs}{kg}$$

$$W\left(\frac{kJ}{kg}\right) = \frac{W(kJ)}{m(kg)} = \frac{1.5124kJ}{0.0077\ \text{kg}} = 196.4\frac{kJ}{kg}$$

Energy density:

$$Density = \frac{W}{V} \Rightarrow \frac{0.420\ Whrs}{1.25\ Litres} \Rightarrow 0.336\frac{Whrs}{Litre}$$

Appendix D – Evaluating True CFM Rating of an Air Compressor

$$Cut\ in\ Pressure = 690\ kPa = 100\ psi$$

$$Cut\ out\ Pressure = 1000\ kPa = 145\ psi$$

$$Time\ Tanken\ from\ Cut\ in\ to\ Cut\ out = 48\ Seconds$$

$$Tank\ volume = 65\ Litres \times 0.264\ Gallons = 17.17\ Gallons$$

$$1\ ft^3 = 7.68\ Gallons$$

$$1\ Atmosphere = 14.7\ psi$$

$$\frac{Tank\ Volume\ (Gallons)}{7.68} = \frac{17.17}{7.68} = 2.23ft^3$$

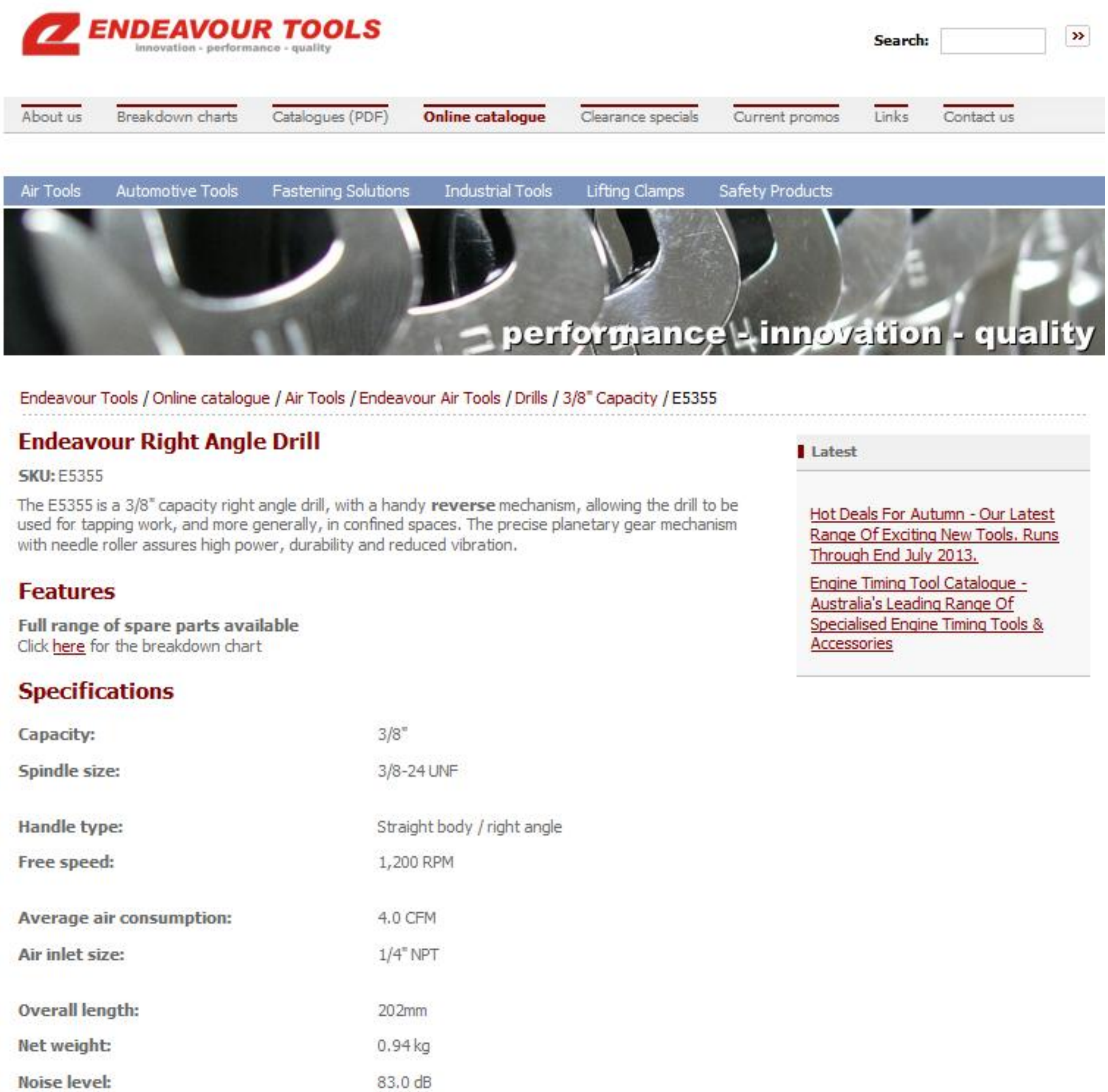
$$\frac{\Delta Pressure}{14.7\ psi} = \frac{145 - 100}{14.7\ psi} = 3.06\ Atm$$

$$2.23ft^3 \times 3.06\ Atm = 6.82ft^3\ per\ 48\ Seconds$$

$$\frac{60}{48} \times 6.82ft^3 = 8.5\ CFM$$

Appendix E – Air Drill Details

Angle Drill



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Endeavour Tools / Online catalogue / Air Tools / Endeavour Air Tools / Drills / 3/8" Capacity / E5355

Endeavour Right Angle Drill

SKU: E5355

The E5355 is a 3/8" capacity right angle drill, with a handy **reverse** mechanism, allowing the drill to be used for tapping work, and more generally, in confined spaces. The precise planetary gear mechanism with needle roller assures high power, durability and reduced vibration.

Features

Full range of spare parts available
Click here for the breakdown chart

Specifications

Capacity:	3/8"
Spindle size:	3/8-24 UNF
Handle type:	Straight body / right angle
Free speed:	1,200 RPM
Average air consumption:	4.0 CFM
Air inlet size:	1/4" NPT
Overall length:	202mm
Net weight:	0.94 kg
Noise level:	83.0 dB

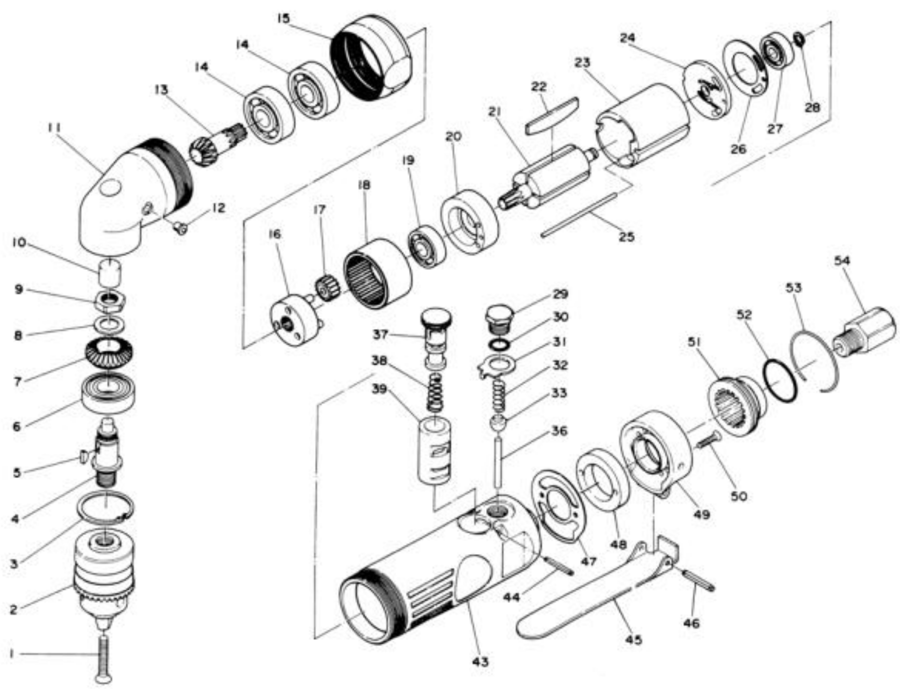
Latest

Hot Deals For Autumn - Our Latest Range Of Exciting New Tools. Runs Through End July 2013.

Engine Timing Tool Catalogue - Australia's Leading Range Of Specialised Engine Timing Tools & Accessories

Parts Breakdown

E5355
3/8" Angle Drill



Ref. No.	Parts No.	Description	Q'ty	Ref. No.	Parts No.	Description	Q'ty
1	988-49	Chuck Screw	1	27	626	Ball Bearing	1
2	22BA	3/8" Drill Chuck w/Handle KK	1	28	JS-6	Retaining Ring	1
3	JO-28	Retaining Ring	1	29	985-39	Valve Screw	1
4	988-6	Spindle	1	30	P-8	O-Ring	1
5	988-8	Key	1	31	985-15	Reverse Retainer	1
6	6001-ZZC2	Ball Bearing	1	32	450-24	Valve Spring	1
7	988-2	Bevel Gear	1	33	930B-12B	Valve	1
8	988-9	Washer	1	36	985-3	Valve Pin	1
9	988-7	Nut	1	37	985-5	Reverse Valve	1
10	KE-45	Needle Bearing	1	38	985-14	Reverse Spring	1
11	988-3	Angle Head	1	39	985-6	Reverse Valve Bush	1
12	115-1	Grease Plug	1	43	988-12	Motor Housing incl. Bush (985-17)	1
13	988-1	Pinion Gear	1	44	25-20	Roll Pin (2.5-20mm)	1
14	6200	Ball Bearing	2	45	985-2	Throttle Lever	1
15	988-11	Lock Ring	1	46	30-24	Roll Pin (3-24mm)	1
16	301-2	Planet Cage incl. Planet Pins (300-21x3)	1	47	985-13	Gasket	1
17	300-13	Planet Gear	3	48	985-41	Muffler	1
18	988-10	Internal Gear	1	49	985-12	Housing Cap	1
19	608	Ball Bearing	1	50	E-M30-120	Screw	2
20	988-4	Front Plate	1	51	620-18	Deflector	1
21	988-5	Rotor	1	52	620-28	O-Ring	1
22	350-16	Rotor Blade	4	53	620-30	Retaining Ring	1
23	217-15	Cylinder	1	54	985-10SC	Inlet Bushing incl. Screen (680-28A)	1
24	217-14	End Plate	1	*55	KK	Chuck Handle for 22BA, SM8K61 & 31902	1
25	200-34	Cylinder Pin	1	*◆56	30221	3/8" Cap. Keyless Chuck (3/8" Thd.)	
26	217-32	Motor Gasket	1				

*Not Shown
◆Option

Printed in Japan
★★★★★Nov. 2000

Straight Drill

SI-5300A Drill

Specification

- 3/8" capacity geared pistol grip drill
- Heavy duty and the best selling model of the drills
- Precise planetary gear mechanism with needle roller assures high power, durability and reducing vibration
- Ergonomic, compact, lightweight design with feather touch trigger for easy centering

Free Speed rpm	2,000
Chuck Size mm/(in.)	10/(3/8)
Spindle Size	3/8-24UNF
Drilling Cap mm/(in.)	10/(3/8)
Out Put Watt	378
Weight kg/(lb)	0.91/(2.01)
Noise Level dBA/(power)	90/(102)
Vibration m/s^2	<2.5
Avg.Air Consumption CFM	3.6
Hose Size mm/(in.)	10/(3/8)

★ : Attachment Inclueded ☆ : Accessories

KD-004 (3/8" Drill Chuck w/Handle KK): Chuck, Handle ★

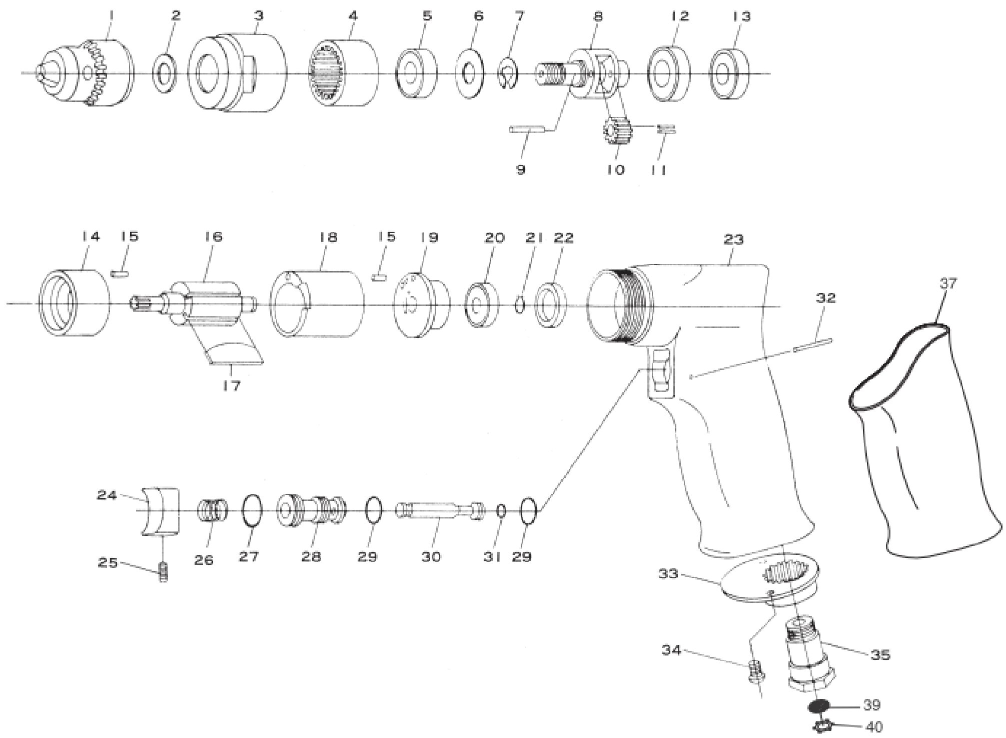
LX10 (Yukiwa) ☆

Parts List & Exploded View drawing

print | << Front page | Back page>> | close

Parts Breakdown

SI-5300A
3/8" Planetary Gear Drill



Ref. No.	Parts No.	Description	Q'ty	Ref. No.	Parts No.	Description	Q'ty
1	22BA	3/8" Drill Chuck w/Handle KK	1	21	JS-6	Retaining Ring	1
2	680-7	Spacer	1	22	680-34	Bearing Cap	1
3	680-8	Clamp Nut	1	23	120-10ASI	Motor Housing	1
4	680-9	Internal Gear	1	24	120-18	Trigger	1
5	EE-3-ZZ	Ball Bearing	1	25	R-M40-60	Set Screw	1
6	680-22	Fiber Washer	1	26	120-31	Valve Spring	1
7	IE-10	Retaining Ring	1	27	P-11	O-Ring	1
8	680-3	Planet Cage	1	28	120-13	Valve Bushing	1
9	680-17	Planet Pin	2	29	P-10	O-Ring	2
10	680-6	Planet Gear	2	30	120-14	Valve Stem	1
11	1500-11-8	Needle Roller	22	31	P-4	O-Ring	1
12	6001	Ball Bearing	1	32	25-20	Roll Pin (2.5ø-20mm)	1
13	608-ZZ	Ball Bearing	1	33	120-11	Deflector	1
14	680-4	Front Plate	1	34	JBM30-80	Screw	2
15	25-5	Roll Pin (2.5ø-5mm)	2	35	120-17	Inlet Bushing	1
16	680-5	Rotor	1	* 36	KK	Chuck Handle for 22BA, SM8K61 & 31902	1
17	350-16	Rotor Blade	4	37	120-35	Housing Cover	1
18	680-1	Cylinder	1	*◆ 38	LX10	3/8" Cap, Keyless Chuck (3/8" Thd.)	
19	680-2	Rear Plate	1	39	680-28A	Screen	1
20	626	Ball Bearing	1	40	CRTW-12	Retainer	1

VOL.2

* Not Shown
◆ Option

Printed in Japan
Oct. 2011

Appendix F – Evaluating True Energy

Angle Drill

Pressure (Pa)	Mass m = PV / RT (kg)	Time during MEP test (seconds)	Power from MEP (W)	New Proportion of Time (seconds)	New Time (seconds)	Energy Output (J)
1000000	0.836					
750000	0.646	10	230		8.00	1840.00
600000	0.532	21	187	0.38	7.88	1472.63
450000	0.418	39	149	0.27	10.64	1584.82
300000	0.304	72.6	80	0.21	15.56	1244.57
150000	0.190	182.4	24	0.18	32.19	772.52
					Total Energy (J)	6914.53
					Total Whr	1.92

Straight Drill

Pressure (Pa)	Mass m = PV / RT (kg)	Time during MEP test (seconds)	Power from MEP (W)	New Proportion of Time (seconds)	New Time (seconds)	Energy Output (J)
1000000	0.836					
750000	0.646	8	463		8.00	3704.00
600000	0.532	16	322	0.38	6.00	1932.00
450000	0.418	36	204	0.27	9.82	2002.91
300000	0.304	66	91	0.21	14.14	1287.00
200000	0.228	123	44	0.13	15.38	676.50
150000	0.190	133	20	0.06	7.82	156.47
					Total Energy (J)	9758.88
					Total Whr	2.71

Appendix G – Battery System Comparison

STEPS	PROCESS	**RESULTS** ***Suggested** based on gel –cell valve regulated lead acid deep cycle low maintenance battery: Max warranty conditions 30% depth of discharge to give 1,100 daily cycles of charge / discharge- column below is cumulative total watt-hr. MAX Life = 3.01 years*
1	Identify total daily use in Watt-hours (Wh)	3,000 Wh/day ***(which by the way for a household is low – Qld household normal is 20–30 kWhr / day)***
2	Identify Days of Autonomy (backup days); multiply Wh/day by this factor	+1 day autonomy = 1 x =2000 Wh/day
3	Identify Depth of Discharge (DoD) and convert to a decimal value. Divide result of Step 2 by this value	30% DoD *(warranty guarantee)* 10,000 Wh
4	De-rate battery bank for ambient temperature effect. Select the multiplier corresponding to the lowest average temperature your batteries will be exposed to. Multiply result from Step 3 by this factor. Result is *minimum Wh capacity* of	De-rating factor for temp = 1 De-rating factor for life loss to 80% SoLC (State of Life Capacity) of discharge over 3 year life before battery collapse = average of 1.11 = 11,000 Wh

<table>
<tr><td></td><td>battery bank:
<table><tr><th>Temp in Degrees C</th><th>Factor</th></tr><tr><td>26+</td><td>1.00</td></tr><tr><td>21</td><td>1.04</td></tr><tr><td>15</td><td>1.11</td></tr><tr><td>10</td><td>1.19</td></tr><tr><td>-1</td><td>1.30</td></tr><tr><td>-6</td><td>1.40</td></tr><tr><td>12</td><td>1.59</td></tr></table></td><td></td></tr>
<tr><td>5</td><td>Divide result from Step 4 by system voltage. Result is the minimum Amp-hour (Ah) capacity of your battery bank.</td><td>916 Ah</td></tr>
<tr><td>6</td><td>Number of batteries</td><td>916 Ah / 200 Ah batteries = 4.5 Batteries</td></tr>
</table>

Appendix H – 9 Volt Battery

PRODUCT DATASHEET

Energizer

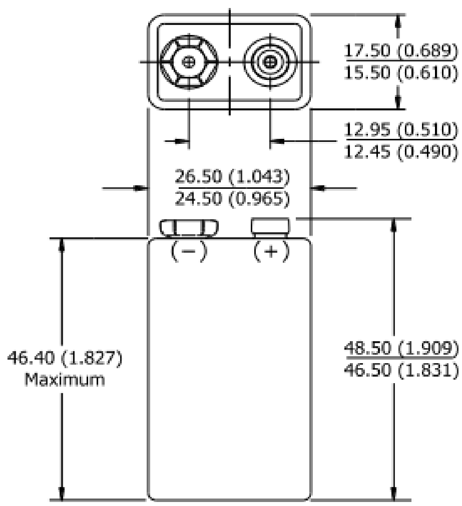
1-800-383-7323 USA/CAN
www.energizer.com

ENERGIZER 522

9V

Industry Standard Dimensions

mm (inches)

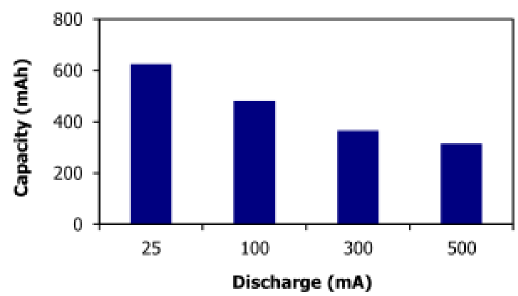


Specifications

Classification:	Alkaline
Chemical System:	Zinc-Manganese Dioxide (Zn/MnO_2) No added mercury or cadmium
Designation:	ANSI-1604A, IEC-6LR61
Nominal Voltage:	9.0 volts
Operating Temp:	-18°C to 55°C (0°F to 130°F)
Typical Weight:	45.6 grams (1.6 oz.)
Typical Volume:	21.1 cubic centimeters (1.3 cubic inch)
Jacket:	Metal
Shelf Life:	5 years at 21°C
Terminal:	Miniature Snap

Milliamp-Hours Capacity

Continuous discharge to 4.8 volts at 21°C



Appendix I – MATLAB® Scripts

%Ideal_Gas_Equations.m

```
% This script calculates the ideal equations for Isothermal and Adabatic
stored energy from
% compressed air. The constants used are to reflect that of an off the
% shelf compressor therefor the maximum pressure was 100kPa.
clc
clear all
close all
format Short eng

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Define Constants
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Pf  = 100:50:1000;%20.6841e+003;  %%  % Final Pressure in kPa
Pi  = 100;                % Initial Pressure in kPa
R   = 0.287;              % Specific Gas Constant kJ/kg.K
AT  = 25;                 % Temperature Degrees Celcius dC
TK  = 273 + AT;           % Absolute temperature Degrees Kelvin K
Ti  = TK;
Vi  = 0.065;              % Inital Volume m3
k   = 1.4;                % Polytropic expansion

%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
% Isothermal Equations which are to be used
%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Free Energy
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
W_Isothermal = R*TK*(log(Pf/Pi));     % W = Energy in Joules/kg
W_kg_Isothermal = W_Isothermal/3600; % Energy stored in kJ/kg

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Volumetric energy density using the ideal gas law:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
V_Isothermal = (R*TK)./Pf;       % Volumetric energy density in m3/kg
V_Litres_Isothermal = V_Isothermal*1000;    % Volumetric energy density in
Litres/kg

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Energy density:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
D_Isothermal = (W_kg_Isothermal*1000)./V_Litres_Isothermal; %D = Density in
Whrs/Litre

%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
% Adabatic Equations which are to be used
%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%To calculate Mass in Kg
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
m = (Pi*Vi)/(R*TK); %m = mass kg

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Temperature (Tf) given by
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tf = Ti*((Pf./Pi).^((k-1)/k)); % Final temperaure of the gas in Kelvins

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Volumetric energy density
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vf_adiabatic = (m*R.*Tf)./Pf;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Free Energy
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
W_adiabatic = ((Pf.*Vf_adiabatic)-(Pi*Vi))/(k-1); % W = Energy in Joules/kg
W_kWhrs_Adiabatic = W_adiabatic/3600; % Energy stored in kWhrs
W_kJkg_Adiabatic = W_adiabatic/m; % W_kWhrs_kg = W_kWhrs/m;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Volumetric energy density using the ideal gas law:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
V_Litres_adiabatic = Vf_adiabatic*1000;   % Volumetric energy density in
Litres/kg
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Energy density:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
D_Adiabatic = (W_kWhrs_Adiabatic*1000)./V_Litres_adiabatic; % D = Density in
Whrs/Litre

%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
% Figures
% Figure 1 and 2 are used for comparison between the two ideal equation
% Figure 1 is the Energy Stored in kJ/kg found using the Adiabatic and
Isothermal Ideal Equations
% Figure 2 is the Specific Power in Whrs/Litre found using the Adiabatic and
Isothermal Ideal Equations
figure(1)
plot(Pf,W_kJkg_Adiabatic,Pf,W_Isothermal)
title('Energy Stored in kJ/kg found using the Adiabatic and Isothermal Ideal
Equations')
xlabel('Pressure (kPa)'),ylabel('Specific Energy (kJ/kg)'),axis('normal')
legend('Adabatic','Isothermal')
%axis([0 1000 0 200])
%text(Pf(:,9),W_kJkg_Adiabatic(:,9),'\leftarrow 122.734
kJ/kg','HorizontalAlignment','left','FontSize',12)
%text(Pf(:,9),W_Isothermal(:,9),'135.339 kJ/kg
\rightarrow','HorizontalAlignment','right','FontSize',12)
figure(2)
plot(Pf,D_Adiabatic,Pf,D_Isothermal)
title('Specific Power in Whrs/Litre found using the Adiabatic and Isothermal
Ideal Equations')
xlabel('Pressure (kPa)'),ylabel('Energy Density (Whrs/Litre)'),axis('normal')
legend('Adabatic','Isothermal')
%axis([0 1000 0 0.7])
```

```
%text(Pf(:,9),D_Adiabatic(:,9),'\leftarrow 0.128
Whrs/Litre','HorizontalAlignment','left','FontSize',12)
%text(Pf(:,9),D_Isothermal(:,9),'0.223 Whrs/Litre
\rightarrow','HorizontalAlignment','right','FontSize',12)
figure(3)
plot(D_Adiabatic,W_kJkg_Adiabatic,D_Isothermal,W_Isothermal)
% title('Specific Power in Whrs/Litre found using the Adiabatic and
Isothermal Ideal Equations')
% xlabel('Pressure (kPa)'),ylabel('Specific Power
(Whrs/Litre)'),axis('normal')
legend('Adabatic','Isothermal')
figure(4)
plot(V_Isothermal,Pf)
title('Specific Power in Whrs/Litre found using the Adiabatic and Isothermal
Ideal Equations')
xlabel('Pressure (kPa)'),ylabel('Specific Power (Whrs/Litre)'),axis('normal')
legend('Adabatic','Isothermal')
```

%Test_Straight_Drill.m

```
% Test on Straight Drill
% This Script is a test conducted on a Straight Air Drill which spins at 2200
RPM @ 90PSI

clc
clear all
close all
format Short eng

% %%PART 1%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% % Below is the equations used to calculate the energy required for the
% % compressor to fill the air receiver. It gives an answer in kilowatts
hours
Volts = 237;         % Voltage of the Compressor
Amps = 5:0.0322:9.7;  % Current reading during filling
time = 0:1:120;       % Time taken to fill the air tank
yi = interp1(Amps,time,'spline');

figure(1)
plot(yi)
title('Current Vs Time of Air Compressor')
xlabel('Time (Sec)'),ylabel('Current (Amps)'),axis('normal')

kW=(Volts.*yi)/1000;    % kilowatts
kWsec=trapz(kW);    % kWsec = kJ = the area under the curve in figure 2
kWhrs=kWsec/3600   % kJ/3600 = kWhrs

%%PART 2%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%* The dyno was tested at different pressure which were regulated the
%* pressures started at 150kPa and increase by 150kPa kPa to 750kPa.

%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
% Variable to complete the calculations

%The radius of the pulley which was attached to the Air motor value in
%Meters
Radius = 0.028;

% conversion from kgm to N.m
kgm_nm = 9.80665;

% Full Air receiver pressure in kPa
X = 1000;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 200kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 2 kg
% * 2.2 kg
% * 2.6 kg
```

```
% * 3 kg
% * 3.6 kg
% * 4.4 kg


% Pressure of the tank at the start of the test was 1000kP. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_200 = [190,200,200,200,210,210];
Pressure_Diff_200 = X - Pressure_final_200;

% Amount of weight in kgs applied during the test
Weight_200 = [2,2.2,2.6,3,3.6,4.4];  % Weight in kgs

% Amount of torque applied in Newton meters
Torque_200 = Weight_200 .* Radius .* kgm_nm;

% RPM of the Air motor at constant loads above
RPM_200 = [630,540,500,460,430,340] ;

% Power output of the Air motor at respective Weight and RPM
Power_200 = Torque_200 .* RPM_200/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_200 = [124.8,123.6,124.2,124.2,123,123 ];

% The total power output of the Air motor During the test
kWsec_T_200 = (Power_200/1000).*Time_200; % kWsec = kJ

kWhrs_200 = kWsec_T_200./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 300kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 2.8 kg
% * 4 kg
% * 4.8 kg
% * 5.4 kg
% * 6 kg

% Pressure of the tank at the start of the test was 1000kP. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_300 = [290,300,310,320,320];
Pressure_Diff_300 = X - Pressure_final_300;

% Amount of weight in kgs applied during the test
Weight_300 = [2.8,4,4.8,5.4,6]; % Weight in kgs

% Amount of torque applied in Newton meters
Torque_300 =  Weight_300.* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
```

```
RPM_300 = [860,740,650,590,500] ;

% Power output of the Air motor at respective Weight and RPM
Power_300 = Torque_300 .* RPM_300/60 * 2*pi;

% Time in seconds to run down tank from 900 to 150kPa at 5 constant loads
Time_300 = [68.4,67.8,67.2,66.6,66.6];

% The total power output of the Air motor During the test
kWsec_T_300 = (Power_300/1000).*Time_300; % kWsec = kJ

kWhrs_300 = kWsec_T_300./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 450kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 4 kg
% * 5 kg
% * 6 kg
% * 7.2 kg
% * 8.6 kg
% * 9 kg

% Pressure of the tank at the start of the test was 1000kP. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_450 = [470,450,460,450,450,430];
Pressure_Diff_450 = X - Pressure_final_450;

% Amount of weight applied in kgs during the test
Weight_450 = [4,5,6,7.2,8, 9];


% Amount of torque applied in Newton meters
Torque_450 = Weight_450 .* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_450 = [1240,1125,1030,960,890,750] ;

% Power output of the Air motor at respective Weight and RPM
Power_450 = Torque_450 .* RPM_450/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_450 = [34,36,35,36,36,38];

% The total power output of the Air motor During the test
kWsec_T_450 = (Power_450/1000).*Time_450; % kWsec = kJ

kWhrs_450 = kWsec_T_450./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 600kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% The dyno test was conducted over the following constant loads
% * 6 kg
% * 7 kg
% * 8 kg
% * 9.6 kg
% * 10.4 kg


% Pressure of the tank at the start of the test was 1000kP. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_600 = [590,600,620,600,600];
Pressure_Diff_600 = X - Pressure_final_600;

% Amount of weight applied in kgs during the test
Weight_600 = [6,7,8.6,9.6,10.4];

% Amount of torque applied in Newton meters
Torque_600 = Weight_600 .* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_600 = [1370,1270,1230,1170,1030] ;

% Power output of the Air motor at respective Weight and RPM
Power_600 = Torque_600.* RPM_600/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_600 = [18,16,15,16,16];

% The total power output of the Air motor During the test
kWsec_T_600 = (Power_600/1000).*Time_600 ;% kWsec = kJ

kWhrs_600 = kWsec_T_600./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 750kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following six constant loads
% * 4 kg
% * 6 kg
% * 8 kg
% * 10 kg
% * 12.6 kg
% * 14.4 kg


% Pressure of the tank at the start of the test was 1000kPa. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_750 = [760,750,750,770,760,760];
Pressure_Diff_750 = X - Pressure_final_750;


% Amount of weight applied in kgs during the test
```

```
Weight_750 = [4,6,8,10,12.6,14.4];

% Amount of torque applied in Newton meters
Torque_750 = Weight_750 .* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_750 = [1980,1490,1430,1380,1280,1020] ;

% Power output of the Air motor at respective Weight and RPM
Power_750 = Torque_750 .* RPM_750/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_750 = [8,9,9,7,8,8];

% The total power output of the Air motor During the test
kWsec_T_750 = (Power_750/1000).*Time_750; % kWsec = kJ

kWhrs_750 = kWsec_T_750./3600;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The following is all the collect data and calculation from above in matrix
%
Results_200 =
[Power_200;Torque_200;RPM_200;Weight_200;Time_200;kWsec_T_200;kWhrs_200;Press
ure_final_200;Pressure_Diff_200]';
Max_200=Results_200(5,:);

Results_300 =
[Power_300;Torque_300;RPM_300;Weight_300;Time_300;kWsec_T_300;kWhrs_300;Press
ure_final_300;Pressure_Diff_300]';
Max_300=Results_300(4,:);

Results_450 =
[Power_450;Torque_450;RPM_450;Weight_450;Time_450;kWsec_T_450;kWhrs_450;Press
ure_final_450;Pressure_Diff_450]';
Max_450=Results_450(5,:);

Results_600 =
[Power_600;Torque_600;RPM_600;Weight_600;Time_600;kWsec_T_600;kWhrs_600;Press
ure_final_600;Pressure_Diff_600]';
Max_600=Results_600(4,:);

Results_750 =
[Power_750;Torque_750;RPM_750;Weight_750;Time_750;kWsec_T_750;kWhrs_750;Press
ure_final_750;Pressure_Diff_750]';
Max_750=Results_750(5,:);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The following
%finds the Maximum power output for each pressure and the
% corresponding time and creates a matrix to be used with the interpolation
% function.
```

```
Max_Power = [Max_200(1),Max_300(1),Max_450(1),Max_600(1),Max_750(1)];
Time = [Max_200(5),Max_300(5),Max_450(5),Max_600(5),Max_750(5)]
%Time = [22,14.9,9.6,2.7,8];


Test2 = Max_Power .* Time

B =sum(Test2)

xi= 0:1:123; % One Seconds intervals

yi = interp1(Time,Max_Power,xi,'cubic');

kW=yi./1000;    % kilowatts

kWSEC=trapz(kW);     % kWsec = kJ = the area under the curve in figure 2

kWhrs
KWhrs=kWSEC/3600    % kJ/3600 = kWhrs

Eff = KWhrs/kWhrs * 100

V = 65 % Volume of 65 litres

DENSITY = KWhrs/V

%
figure (2)
plot(Time,Max_Power,'+',xi,yi)
title('Power out at all Pressures')
xlabel('Time (Sec)'),ylabel('Power (Watts)'),axis('normal')
grid on

%
%%%PART 3
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Part of the script is to find the maximum RPM of the test to get a
% Air Motor Speed vs Pressure curve to find out the tank usage in another
% test

EFF_RPM = [Max_200(3),Max_300(3),Max_450(3),Max_600(3),Max_750(3)];
Pressure = [Max_200(8),Max_300(8),Max_450(8),Max_600(8),Max_750(8)];

xii= 0:100:1000;
yii = interp1(Pressure,EFF_RPM,xii,'spline');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Part of the script interpolated the Max Power over Pressure used.

xiii= 0:10:800;
yiiii = interp1(Pressure,Max_Power,xiii,'cubic');
```

```
% This figure show two graphs the top is of the Pressure used vs the RPM
% achieved and the bottom is of the Max Power vs the Pressure
%
figure (3)
subplot(2,1,1)
plot(Pressure,EFF_RPM,'+',xii,yii)
title('Air Motor Speed Vs Pressure')
xlabel('Pressure (kPa)'),ylabel('Speed (RPM)'),
axis([0 800 0 1500])
grid on

subplot(2,1,2)
plot(Pressure,Max_Power,'o',xiii,yiiii)
title('Air Motor Power Vs Pressure')
xlabel('Pressure (kPa)'),ylabel('Power (W)'),
axis auto
grid on
```

%Testing Angle Drill.m

```
% Test on Angle Drill
% This Script is a test conducted on a Angle Air Drill which spins at 1200
RPM @
% 90PSI
clc
clear all
close all
format Short eng


% %%PART 1%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Below is the equations used to calculate the energy required for the
% compressor to fill the air receiver. It gives an answer in kilowatts hours

Volts = 237;         % Voltage of the Compressor
Amps = 5:0.0322:9.7;  % Current reading during filling
time = 0:1:120;       % Time taken to fill the air tank
yi = interp1(Amps,time,'spline');


figure(1)
plot(yi)
title('Current Vs Time of Air Compressor')
xlabel('Time (Sec)'),ylabel('Current (Amps)'),axis('normal')

kW=(Volts.*yi)/1000;    % kilowatts
kWsec=trapz(kW);     % kWsec = kJ = the area under the curve in figure 2
kWhrs=kWsec/3600 ;  % kJ/3600 = kWhrs


%%PART 2%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%* The dyno was tested at different pressure which were regulated the
%* pressures started at 150kPa and increase by 150kPa kPa to 750kPa.

%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
% Variable to complete the calculations
% The radius of the pulley which was attached to the Air motor value in
% meters
Radius = 0.028;

% conversion from kgm to N.m
kgm_nm = 9.80665;

% Full Air receiver pressure in kPa
X = 1000;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 150kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 0.8 kg
```

```
% * 1 kg
% * 1.6 kg
% * 2.4 kg
% * 3 kg
% * 3.2 kg
% * 3.4 kg

% Pressure of the tank at the start of the test was 1000kPa. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_150 = [140,180, 150, 170,170, 150, 150];
Pressure_Diff_150 = X - Pressure_final_150;

% Amount of weight applied in kgs during the test
Weight_150 = [0.8,1,1.6,2.4,3,3.2,3.4];

% Amount of torque applied in Newton meters
Torque_150 = Weight_150 .* Radius .* kgm_nm;

% RPM of the Air motor at constant loads above
RPM_150 = [380,350,330,300,285,230, 160];

% Power output of the Air motor at respective Weight and RPM
Power_150 = Torque_150 .* RPM_150/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_150 = [184.8,181.8,183.6,183,182.4,184.2,183];

% The total power outout of the Air motor suring the test
kWsec_T_150 = (Power_150/1000).*Time_150; % kWsec = kJ

kWhrs_150 = kWsec_T_150./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 300kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 1.4 kg
% * 3 kg
% * 4 kg
% * 5.6 kg
% * 6.6 kg
% * 7 kg

% Pressure of the tank at the start of the test was 1000kPa. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_300 = [290,300,320,300,310,300];
Pressure_Diff_300 = X - Pressure_final_300;

% Amount of weight applied in kgs during the test
Weight_300 = [1.4,3,4,5.6,6.6,7];

% Amount of torque applied in Newton meters
```

```
Torque_300 =  Weight_300.* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_300 = [680,600,570,500,380,230];

% Power output of the Air motor at respective Weight and RPM
Power_300 = Torque_300 .* RPM_300/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_300 = [73.8,73.2,72.6,72.6,72.6,72];


% The total power output of the Air motor during the test
kWsec_T_300 = (Power_300/1000).*Time_300; % kWsec = kJ

kWhrs_300 = kWsec_T_300./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 450kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 3 kg
% * 5 kg
% * 7 kg
% * 8.6 kg
% * 9.6 kg
% * 10.6 kg

% Pressure of the tank at the start of the test was 1000kPa. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_450 = [460,470,450,450,460,470];
Pressure_Diff_450 = X - Pressure_final_450;

% Amount of weight applied in kgs during the test
Weight_450 = [3,5,7,8.6,9.6,10.6];

% Amount of torque applied in Newton meters
Torque_450 = Weight_450.* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_450 = [760,700,650,605,520,405] ;

% Power output of the Air motor at respective Weight and RPM
Power_450 = Torque_450 .* RPM_450/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_450 = [38,37,39,39,38,37];

% The total power output of the Air motor during the test
kWsec_T_450 = (Power_450/1000).*Time_450; % kWsec = kJ

kWhrs_450 = kWsec_T_450./3600;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 600kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 4 kg
% * 6 kg
% * 7.6 kg
% * 9.6 kg
% * 10.6 kg
% * 11.4 kg

% Pressure of the tank at the start of the test was 1000kPa. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_600 = [590,590,620,600,580,600];
Pressure_Diff_600 = X - Pressure_final_600;

% Amount of weight applied in kgs during the test
Weight_600 = [4,6,7.8,9.6,10.6,11.4];

% Amount of torque applied in Newton meters
Torque_600 = Weight_600.* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_600 = [926,850,750,680,556,450] ;

% Power output of the Air motor at respective Weight and RPM
Power_600 = Torque_600 .* RPM_600/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_600 = [22,22,20,21,23,21];

% The total power output of the Air motor during the test
kWsec_T_600 = (Power_600/1000).*Time_600 ;% kWsec = kJ

kWhrs_600 = kWsec_T_600./3600;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pressure Regulated at 750kPa
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The dyno test was conducted over the following constant loads
% * 5 kg
% * 6 kg
% * 7 kg
% * 8 kg
% * 9 kg
% * 11 kg
% * 12 kg

% Pressure of the tank at the start of the test was 1000kPa. The following
data is the
% difference from a full tank to approximately the regulated pressure
Pressure_final_750 = [760,750,760,750,760,750,760];
Pressure_Diff_750 = X - Pressure_final_750;
```

```
% Amount of weight applied in kgs during the test
Weight_750 = [5,6,7,8,9,11,12];

% Amount of torque applied in Newton meters
Torque_750 =  Weight_750.* Radius .* kgm_nm ;

% RPM of the Air motor at constant loads above
RPM_750 = [894,850,830,790,760,730,650] ;

% Power output of the Air motor at respective Weight and RPM
Power_750 = Torque_750 .* RPM_750/60 * 2*pi;

% Time in seconds to run down tank from 1000 to 150kPa at 5 constant loads
Time_750 = [9,10,9,10,9,10,9];

% The total power output of the Air motor during the test
kWsec_T_750 = (Power_750/1000).*Time_750; % kWsec = kJ

kWhrs_750 = kWsec_T_750./3600;
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% the following is all the collect data and calculation from above in matrix
%
Results_150 =
[Power_150;Torque_150;RPM_150;Weight_150;Time_150;kWsec_T_150;kWhrs_150;Press
ure_final_150;Pressure_Diff_150]';
Max_150=Results_150(5,:);

Results_300 =
[Power_300;Torque_300;RPM_300;Weight_300;Time_300;kWsec_T_300;kWhrs_300;Press
ure_final_300;Pressure_Diff_300]';
Max_300=Results_300(4,:);

Results_450 =
[Power_450;Torque_450;RPM_450;Weight_450;Time_450;kWsec_T_450;kWhrs_450;Press
ure_final_450;Pressure_Diff_450]';
Max_450=Results_450(4,:);

Results_600 =
[Power_600;Torque_600;RPM_600;Weight_600;Time_600;kWsec_T_600;kWhrs_600;Press
ure_final_600;Pressure_Diff_600]';
Max_600=Results_600(4,:);

Results_750 =
[Power_750;Torque_750;RPM_750;Weight_750;Time_750;kWsec_T_750;kWhrs_750;Press
ure_final_750;Pressure_Diff_750]';
Max_750=Results_750(6,:);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The following finds the Maximum power output for each pressure and the
% corresponding time and creates a matrix to be used with the interpolation
% function.

Max_Power = [Max_150(1),Max_300(1),Max_450(1),Max_600(1),Max_750(1)];
```

```
Time = [Max_150(5),Max_300(5),Max_450(5),Max_600(5),Max_750(5)];

xi= 0:1:182; % One Seconds intervals

yi = interp1(Time,Max_Power,xi,'cubic');

kW=yi./1000;   % kilowatts

kWSEC=trapz(kW);    % kWsec = kJ = the area under the curve in figure 2

kWhrs
KWhrs=kWSEC/3600   % kJ/3600 = kWhrs

Eff = KWhrs/kWhrs * 100

V = 65 % Volume of 65 litres

DENSITY = KWhrs/V

figure (2)
plot(Time,Max_Power,'+',xi,yi)
title('Power out at all Pressures')
xlabel('Time (Sec)'),ylabel('Power (Watts)'),axis('normal')
grid on
% %
%
%%%PART 3
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Part of the script is to find the maximum RPM of the test to get a
% Air Motor Speed vs Pressure curve to find out the tank usage in another
% test


EFF_RPM = [Max_150(3),Max_300(3),Max_450(3),Max_600(3),Max_750(3)];
Pressure = [Max_150(8),Max_300(8),Max_450(8),Max_600(8),Max_750(8)];

xii= 0:100:1000;
yii = interp1(Pressure,EFF_RPM,xii,'spline');

F = fliplr([xii;yii])'; % To find out what the pressures and RPM for Power
over Pressure
xlswrite('SpeedVPressure.xls', F);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Part of the script interpolated the Power over Pressure.

xiii= 0:10:800;
yiii = interp1(Pressure,Max_Power,xiii,'cubic');

% This figure show two graphs the top is of the Pressure used vs the RPM
% achieved and the bottom is of the Max Power vs the Pressure

figure (3)
subplot(2,1,1)
plot(Pressure,EFF_RPM,'+',xii,yii)
```

```
title('Air Motor Speed Vs Pressure')
xlabel('Pressure (kPa)'),ylabel('Speed (RPM)'),
axis([0 800 0 800])
grid on

subplot(2,1,2)
plot(Pressure,Max_Power,'o',xiii,yiii)
title('Air Motor Power Vs Pressure')
xlabel('Pressure (kPa)'),ylabel('Power (W)'),
axis([0 800 0 800])
grid on

%
```

%Tank Usage.m

```
clc
clear all
close all
format Short eng

%^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
% Variable to compelete the calculations

%The radius of the pully which was attached to the Air motor value in
%Meters
Radius = 0.028;

% conversion from kgm to N.m
kgm_nm = 9.80665;


% %%PART 1%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% % Below is the equations used to calcutlate the energy required for the
% % compressor to fill the air reciever. It gives an answer in kilowatts
hours
%
Volts = 237;  % Voltage of the Compressor
Amps = 5:0.0322:9.7;  % Current reading during filling
time = 0:1:120;
yi = interp1(Amps,time,'spline');


% figure(1)
% plot(yi)
% title('Current Vs Time of Air Compressor')
% xlabel('Time (Sec)'),ylabel('Current (Amps)'),axis('normal')

kW=(Volts.*yi)/1000;    % kilowatts
kWsec=trapz(kW);    % kWsec = kJ = the area under the curve in figure 2
kWhrs=kWsec/3600   % kJ/3600 = kWhrs




% STRAIGHT DRILL TEST NO LOAD FULL TANK TO EMPTY - 1000kPa - Regulator
% set at 750kPa

Pressure_SD_NL = [900,800,700,600,500,400,300,200,100,0];
RPM_SD_NL = [2600,2300,2018,1900,1770,1540,1310,940,435,0];
Time_SD_NL = [3,5,8,13,18,24,33,49,67.8,78];


% ANGLE DRILL TEST NO LOAD FULL TANK TO EMPTY - 1000kPa - Regulator
% set at 750kPa
```

```
Pressure_AD_NL = [900,800,700,600,500,400,300,200,100,0];
RPM_AD_NL = [1250,1195,1100,1020,977,835,650,450,150,0];
Time_AD_NL = [4,8,12,17,22,30,45,64,79.8,81];

% % Figure 1 is the results of a no load test on the air motor
% figure (1)
% subplot(2,1,1)
% plot(Time_SD_NL,Pressure_SD_NL)
% title('Straight Drill No Load')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% subplot(2,1,2)
% plot(Time_AD_NL,Pressure_AD_NL)
% title('Angle Drill No Load')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% %
%
% % STRAIGHT DRILL TEST LOADED FULL TANK TO EMPTY - 1000kPa - Regulator
% % set at 750kPa
%
% Pressure_SD_L = [900,800,700,600,500,400,300,200,100,0]; % Air was not
usabe after 200 kPa
% RPM_SD_L = [1360,1340,1260,1080,930,660,216,110,50,0 ];
% Time_SD_L = [3,5,8,12,18,28,41,43,46,47];
% Weight_SD_L  = [13,12.6,12.2,9.6,8.4,6.0,0,0,0,0];

%
Pressure_SD_L = [900,800,700,600,500,400]; % Air was not usabe after 200 kPa
RPM_SD_L = [1360,1340,1260,1080,930,660 ];
Time_SD_L = [3,5,8,12,18,28];
Weight_SD_L  = [13,12.6,12.2,9.6,8.4,6.0];



% Amount of torque applied in Newton meters
Torque_SD_L = Weight_SD_L .* Radius .* kgm_nm ;

% Power output of the Air motor at respective Weight and RPM
Power_SD_L = Torque_SD_L .* RPM_SD_L/60 * 2*pi;

xi= 0:1:28;
yi = interp1(Time_SD_L,Power_SD_L,xi,'cubic');

kW_SD_L=yi./1000;    % kilowatts


kWSEC_SD_L=trapz(kW_SD_L);     % kWsec = kJ = the area under the curve in
figure 2

kWhrs;
KWhrs_SD_L=kWSEC_SD_L/3600    % kJ/3600 = kWhrs

Eff_SD_L = KWhrs_SD_L/kWhrs * 100
```

```
% % ANGLE DRILL TEST LOADED FULL TANK TO EMPTY - 1000kPa - Regulator
% % set at 750kPa
%
% Pressure_AD_L = [900,800,700,600,500,400,300,200,100,0]; % Air was not
usabe after 200 kPa
% RPM_AD_L = [800,790,770,730,664,515,348,114,20,0 ];
% Time_AD_L = [4,7,11,16,23,33,46,60,64,66];
% Weight_AD_L  = [11.2,11,10.8,9.6,9,8.4,0,0,0,0];

Pressure_AD_L = [900,800,700,600,500,400]; % Air was not usabe after 200 kPa
RPM_AD_L = [800,790,770,730,664,515 ];
Time_AD_L = [4,7,11,16,23,33,];
Weight_AD_L  = [11.2,11,10.8,9.6,9,8.4];




% Amount of torque applied in Newton meters
Torque_AD_L = Weight_AD_L .* Radius .* kgm_nm ;

% Power output of the Air motor at respective Weight and RPM
Power_AD_L = Torque_AD_L .* RPM_AD_L/60 * 2*pi;

xii= 0:1:33;
yii = interp1(Time_AD_L,Power_AD_L,xii,'cubic');

kW_AD_L=yii./1000;   % kilowatts


kWSEC_AD_L=trapz(kW_AD_L);     % kWsec = kJ = the area under the curve in
figure 2

kWhrs
KWhrs_AD_L=kWSEC_AD_L/3600    % kJ/3600 = kWhrs

Eff_AD_L = KWhrs_AD_L/kWhrs * 100




figure (2)
subplot(2,1,1)
plot(Time_SD_L,Power_SD_L,'+',xi,yi)
%plot(xii,yii,xi,yi)

title('Power out at all Pressures')
xlabel('Time (Sec)'),ylabel('Power (Watts)'),
axis('normal')
grid on
legend('Straight Drill')
%
```

```
subplot(2,1,2)
plot(Time_AD_L,Power_AD_L,'+',xii,yii)
title('Power out at all Pressures')
xlabel('Time (Sec)'),ylabel('Power (Watts)'),
axis('normal')
grid on
legend('Angle Drill')


% %
% % % Figure 2 is of the air motor test when the load is applied
% figure (2)
% subplot(2,1,1)
% plot(Time_SD_L,Pressure_SD_L)
% title('Straight Drill Loaded')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% subplot(2,1,2)
% plot(Time_AD_L,Pressure_AD_L)
% title('Angle Drill Loaded')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% % %
%
%
% % % Figure 3 is all the test together to compare
% figure (3)
% subplot(2,2,1)
% plot(Time_SD_NL,Pressure_SD_NL)
% title('Straight Drill No Load')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% subplot(2,2,2)
% plot(Time_AD_NL,Pressure_AD_NL)
% title('Angle Drill No Load')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
%
% subplot(2,2,3)
% plot(Time_SD_L,Pressure_SD_L)
% title('Straight Drill Loaded')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% subplot(2,2,4)
% plot(Time_AD_L,Pressure_AD_L)
% title('Angle Drill Loaded')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
%
%
%
% % Figure 4 is a comparision of the No Load test between the Angle and
% % straight drill and the time it lasted for
% figure (4)
% subplot(2,1,1)
% plot(Time_SD_NL,Pressure_SD_NL,Time_SD_L,Pressure_SD_L)
% title('Straight Drill')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% legend('No Load','Loaded')
% subplot(2,1,2)
% plot(Time_AD_NL,Pressure_AD_NL,Time_AD_L,Pressure_AD_L)
% title('Angle Drill')
```

```
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% legend('No Load','Loaded')
%
%
% % Figure 4 is a comparision of a Loaded test between the Angle and
% % straight drill and the time it lasted for
% figure (5)
% subplot(2,1,1)
% plot(Time_AD_NL,Pressure_AD_NL,Time_SD_NL,Pressure_SD_NL)
% title('No Load Test')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% legend('Angle Drill','Straight Drill')
% subplot(2,1,2)
% plot(Time_AD_L,Pressure_AD_L,Time_SD_L,Pressure_SD_L)
% title('Loaded Test')
% xlabel('Time (Sec)'),ylabel('Pressure (kPa)'),axis('normal')
% legend('Angle Drill','Straight Drill')

% The following finds the kilowatt hours per litre of the dyno system

KWhrs_Litre_AD = KWhrs_AD_L /65  % Angle Drill

KWhrs_Litre_SD = KWhrs_SD_L /65  % Straight Drill
```