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ELECTRIC MINES OF THE FUTURE – A MULTIPLE CRITERIA SELECTION PROCESS FOR A REMOTE MINE SITE ENERGY STORAGE SOLUTION

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ABSTRACT

This project involved the creation and validation of a renewable-energy-storage selection model for remote operations such as mine sites. It is intended to be used in the initial investigation of possible energy storage solutions for these operations, and to be used by anyone within that operation; whether they have a technical background or not. The available energy storage technologies have been assessed to generate a set of viable options that could be implemented as part of a storage solution. A number of multiple criteria decision models have been assessed to find a method that can deal with the many criteria and alternatives involved with such a decision. An Analytical Hierarchy Process (AHP) approach and a decision tree diagram are used to provide a number of solution sets. The AHP model was used with 4 criteria; power output characteristics, required space for installation, expected lifetime of operation and operational temperature range. These were used to create 4 specific scenarios, each one specifying a criteria as a priority. A recommendation is provided for each of these scenarios. The decision tree diagram utilises the same 4 criteria, expanding on them by assigning specific ranges to them. This allows for a higher level of specificity by the user, the result being a more tailored list of energy storage solutions.

ACKNOWLEDGEMENTS

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NOMENCLATURE

AHI	Aqueous Hydrogen Ion Batteries
AHP	Analytical Hierarchy Process
ALA	Advanced Lead Acid Batteries
CAES	Compressed Air Energy Storage
CES	Cryogenic Energy Storage
CR	Consistency Ratio
DM	Decision Maker
GP	Goal Programming
H_2	Hydrogen Energy Storage
kW/ MW	Kilo Watt/ Mega Watt
kWh/ MWh	Kilo Watt hour/ Mega Watt hour
LIO	Lithium Ion Batteries
MCDA/P/M	Multiple Choice Decision Analysis/ Process/ Model
OM	Outranking Models
PCM	Pairwise Comparison Matrix
PHES	Pumped Hydro Energy Storage
TCSE	Thermal Concentrating Solar Energy
TPHE	Thermal Pumped Heat Electrical
VM	Value Measurement
ZHC	Zinc Hybrid Cathode Batteries

1. INTRODUCTION

1.1 MOTIVATION

Currently the majority of the world's population that live in industrialised areas access electricity via a utility operated, large scale, centralised grid (Gordon, 2013). Renewable energy constitutes approximately 22.1% of this produced electricity (Zervos, 2014) globally and, though this is not a majority amount, it forms a crucial part of the power generation scene by allowing communities that are islanded from the grid access to power. Examples of this type of community are the remote mine sites of Australia that require provision of baseload power in order to function; these sites are the focal point of this paper. The choices related to how these remote mine sites generate power is changing. Where it was once only fossil fuels under consideration now renewables enter the decision as well. This is due to more renewable power generation and storage methods gaining maturity, resulting in lower prices and higher efficiencies. This is in contrast to the increasing costs of extracting and utilising fossil fuels (Gordon, 2013), and the levels of investment needed to transport this to site via gas pipelines, long distance power lines for transmission or some other means; none of which are generally necessary with renewables.

The necessity for power storage becomes most apparent when you contrast a power load profile for a mine site over the course of 1 day (displayed in Figure 1 – Power Load Profile for a Mine Site over 1 Day) against a power output plot for a renewable energy source (a day's output for a photovoltaic system is shown in Figure 2 below). Figure 1 shows the varying level of power load over 10 minute intervals for a Western Australian mine site, illustrating the reasonably constant power requirement (there are no severe spikes in the load level). Figure 2 demonstrates the variation in output of photovoltaics and lets us conclude that any energy source with such intermittency cannot be used by itself to supply baseload power. It is evident that the excess power generated during peak times needs to be stored so that it can be utilised in times of low generation, so as to maintain baseload power to the mine site. Energy storage is found to mitigate the problem of imbalances between power generation and demand, whilst also reducing the amount of excess energy that is wasted (Gordon, 2013). This is the reason behind the need for energy storage, and the need for an easy-to-utilise and effective storage decision process. For many in the industry the options for energy storage are unknown, and their associated investment requirements in terms of dollar amount and time are unfamiliar. This paper aims to elucidate these points, so as to make the initial stages of renewable energy storage investigation easier for industry. A major aspect of this is dealing with the decision problem that arises from having many alternative forms of storage, and many criteria against which they can be assessed.

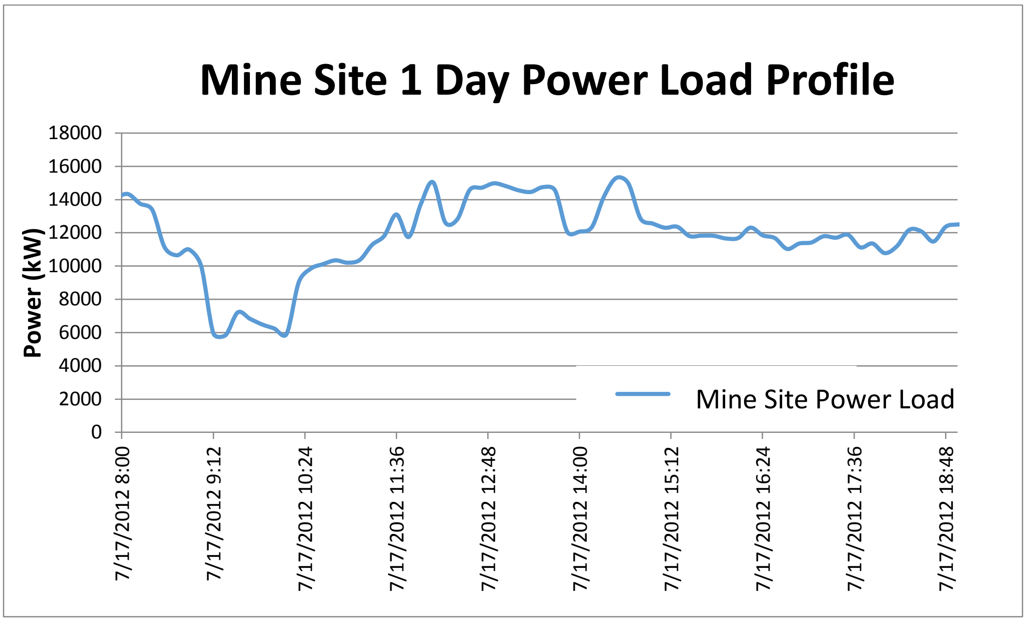


Figure 1 – Power Load Profile for a Mine Site over 1 Day

(Courtesy of Harries (2014))

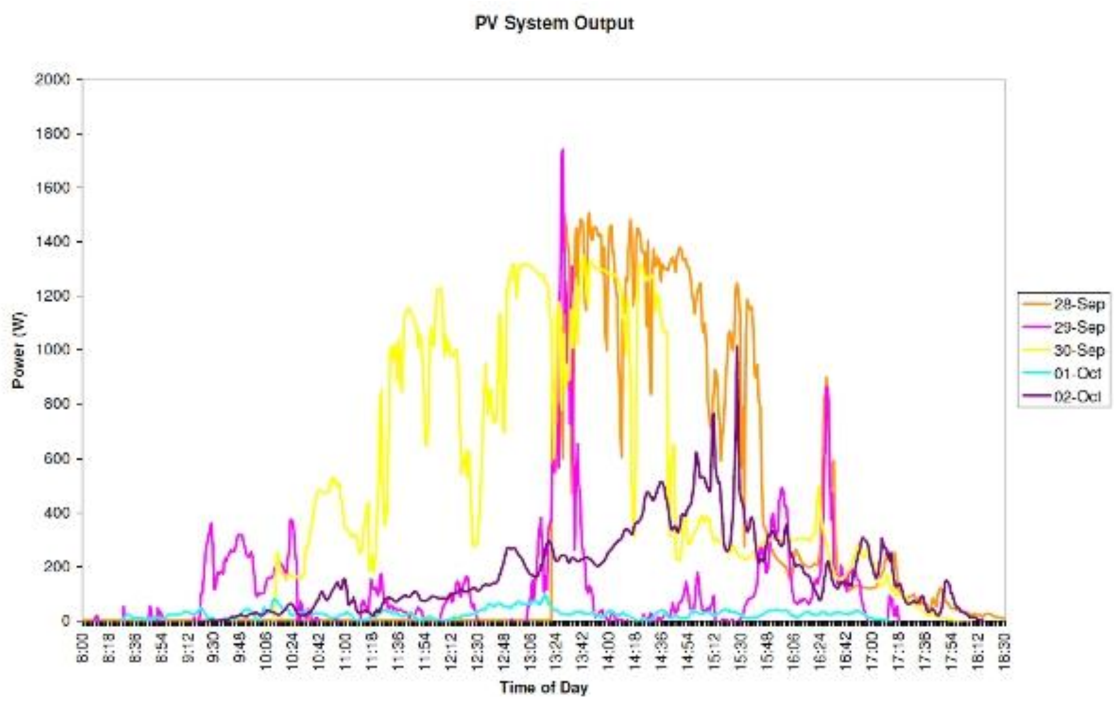


Figure 2 - Power Output Profile for a PV System over 1 day

(PuntoSigma, 2012)

1.2 Overview

The difficulty in selecting an appropriate storage method stems from the numerous assessment criteria and alternative solutions that are part of the decision. These complexities are in part due to the change in paradigm of what must be considered upon selection. Where once it was only the bottom line (economic aspects) that needed to be considered, now considering the triple bottom line has become the norm; this involves economic, social and environmental aspects. To aid in dealing with the increasingly multifaceted decision problems in the scientific and commercial world, such as selecting an energy storage method, Multiple Criteria Decision Analysis (MCDA) models were created. The primary aim of this thesis is to assess MCDA models in order to select an appropriate model upon which to build the energy storage decision process, and to then create this process.

The amount and type of criteria upon which the alternative solutions will be judged determines the type of MCDA model that is most appropriate to be used. At the design stage it is important to define the problem, the objectives, any points that may cause conflict (for example disparate preferences), the level of uncertainty and the key issues; these aspects will affect how the process is framed. The criteria are then be weighted. Weighting demonstrates the relative importance of each criterion in the multiple criteria problem and enables the mechanism for evaluation of the alternatives. Constructing the evaluation matrices follows, which allows " the essence of the problem to be extracted from the complex picture drawn up, so that the problem can be assessed adequately" (Mateo, 2012, p. 9). Lastly the appropriate method is applied in order to ascertain the ranking of the alternatives.

Exploring the possible MCDA methods, in conjunction with methods for energy storage, so that a decision process can be created provides both opportunities and challenges. The challenges are determining which of the many criteria are useful for assessment of the alternatives, and selecting an appropriate MCDA model that returns meaningful, easily understood recommendations. The opportunity is that there is currently no such process available for energy storage within the mining industry, and so the creation of this process will be a contribution to the industry.

1.3 Objectives

The specific objectives can be summarised as follows;

1. Assess available energy storage methods to identify the current state of technologies and pending research into improvements, with special attention paid to those that are applicable to mine sites.

2. Explore current Multiple Criteria Decision Models (MCDM). Analyse any specific applications of these models to the selection of storage technologies for mine sites or related scenarios.

    a. Identify an appropriate MCDM that can be used to reach a recommendation for the energy storage decision problem.

3. Develop a non-technical decision process for people in the mining industry. It should ascertain the most appropriate energy storage solution for a chosen mine site, this includes;
    a. Identify which technologies are acceptable for forming part, or all, of a solution.
    b. Analyse criteria against which possible technologies can be assessed, depending on mine site requirements

4. Critically assess and review results and identify areas of further research.

2. LITERATURE REVIEW – MULTI-CRITERIA DECISION MODELS

In order to generate a selection process for the mining industry, it is important to first look at what models and processes have been created to deal with the selection problem between energy storage technologies. This requires looking at what models there are to use in addressing this type of decision, and then at any specific applications of these models to mine sites. This will reveal if it is indeed necessary to generate a new simple model for selecting a storage solution for a specific mine site.

2.1 *USE OF MULTICRITERIA DECISION ANALYSIS METHODS FOR ENERGY PLANNING PROBLEMS* BY E. LØKEN 2007

To begin with, the problem of selecting an ideal storage solution is defined as a 'choice problem' by Roy (1981), this problem type aims to select the single best solution (if only one criterion is being considered), or at least reduce the total set of alternatives to an optimal subset; which is the case for most real world scenarios. Models that come under the general heading of Multiple Criteria Decision Analysis (MCDA) are used to deal with such problems. These models aid decision makers in ordering their preferences and generating a decision in scenarios where there are many, sometimes conflicting, criterion (Løken, 2007).

MCDA methods can be classified in numerous ways, one of the more popular that has been adopted from Belton and Stewart (2002) is the following categorisation in to three broad schools of thought;

- <u>Goal programming (GP), aspiration level and reference level models</u>
  Commonly referred to as simply GP methods, the basis of these approaches is to try and determine the alternatives (storage technologies in this case) that in some sense align most closely to a predetermined goal or aspiration level. Regularly GP methods are used during the initial phase of a multi-criteria decision process to screen out unsuitable alternatives in a quick and efficient manner. As an example, goal programming assigns a target value to each criteria. Any unwanted deviations of the alternatives from this target value are minimised where possible until there is either zero deviation or the alternative is within an acceptable margin of the target value. GP is unable to deal with qualitative criteria, as each one must be associated with a measurable attribute. This means GP has to be combined with another method to deal with qualitative and quantitative criteria jointly (Jones and Tamiz, 2010, Løken, 2007). This factor makes it less appealing as a possible approach to the energy storage decision problem due to the

possibility that qualitative criteria may want to be use in the assessment of the storage methods at a later date.

- Outranking models (OM)

  OM methods construct a set of preference relations (referred to as outranking relations) among the alternatives evaluated over several criteria. These are mostly generated through pairwise comparisons, most often following the concordance-discordance principle. Utilising this principle often gives rise to binary relations (BR) which are not complete (x may have a BR with y, but y does not have a BR with x) or transitive (x BR with y, y BR with z, x NOT-BR with z). Utilising OM's to reach an easy to convey and conclusive decision can therefore be a challenging task (Bouyssou, 2009), though using an appropriate model can reduce this difficulty. For the energy storage decision problem, the Analytical Hierarchy Approach (AHP) is an example of this, and will be discussed later in this section.

- Value Measurement (VM) Models

  Each criteria that will be used to compare alternatives is given a weighting that illustrates how important it is to the decision maker. All criteria are then analysed for each alternative (criteria weighting multiplied by the alternatives performance in that criteria) and summed to give a total performance value for that alternative across all criteria. This value is a numerical score which produces a preference ordered list of the alternatives (Løken, 2007). Value measurement models appear to be the most applicable to the decision problem being faced, as they can deal with both qualitative and quantitative criteria, they reach a final solution relatively easily and this solution is in a referenced list which is easy to convey, which would be useful when illustrating different technologies to members in the mining industry.

A point worthy of note that Løken asserts is the presence of a "black box" effect, where if one cannot understand the process used to reach a conclusion they are more likely to be distrustful of that conclusion. This means that the decision process selected must be easy to follow, so that any recommendation will be trusted.

Now that there is some familiarity with the types of decision models that are available, a look at how these have been applied to energy storage solution decisions, and solutions for mine sites, is needed.

2.2 *MULTIPLE CRITERIA ANALYSIS FOR ENERGY STORAGE SELECTION* BY A. BARIN ET AL. 2011

In this paper Barin et al. (June 2011) utilises the AHP approach, along with fuzzy multi-sets and multi-rules, to determine an optimal storage solution. Where AHP is an OM process, fuzzy multi-sets and multi-rules comes under the VM category, which illustrates that a decision problem can often be dealt with in various ways. Barin looks at a set of storage technologies to ascertain the most appropriate storage solution, with a priority being placed on power quality. To determine the solution he employs a number of criteria including; power quality, load management, technical maturity, efficiency, cost and environmental impacts. After applying the AHP model the output was a ranked list, from first to fourth, of each of the alternatives; these can be seen in Table 1 – Final Ranking under AHP

. This table lists the alternative forms of storage in the far left column, Compressed Air Energy Storage (CAES) at the top followed by Pumped Hydro Storage (PHS) and so on. These alternatives are assessed against the list of criteria in the top row, starting with efficiency (EF), load management (LM), technical maturity (TM) and so on. Barin goes on to carry out a similar simulation with the fuzzy multi-sets and multi-rules to cross-check the ranking results from the AHP method. Working with the same data for both simulations the second method returns the same results as AHP (this is displayed in Table 2 - Final Rankings under AHP and Fuzzy multi-sets and multi-rules

). One of the major outcomes by Barin et al. in this paper is the verification that the relationship between values and judgements is respected by AHP analysis (at least in this specific case study). This adds weight to the original results and suggests that AHP or fuzzy multi-sets and multi-rules by themselves is adequate in dealing with such a decision problem.

Table 1 – Final Ranking under AHP

(Barin et al., June 2011)

	EF	LM	TM	COST	IMPAC	PQ	FRW	CL
CAES	0.01	0.02	0.02	0.00	0.00	0.01	0.057	4th
PHS	0.01	0.02	0.02	0.00	0.00	0.01	0.055	4th
H_2	0.00	0.05	0.00	0.00	0.00	0.09	0.148	2nd
FLY	0.04	0.01	0.02	0.01	0.01	0.07	0.167	1st
SUP	0.04	0.00	0.01	0.00	0.01	0.04	0.103	3rd
LITH	0.04	0.04	0.01	0.00	0.01	0.06	0.164	1st
NaS	0.02	0.04	0.00	0.00	0.00	0.09	0.151	2nd
VRB	0.02	0.04	0.00	0.00	0.00	0.09	0.156	2nd

Table 2 - Final Rankings under AHP and Fuzzy multi-sets and multi-rules

(Barin et al., June 2011)

	AHP		Fuzzy	
	FRW	CL	FRW	CL
CAES	0.057	4th	0.381	4th
PHS	0.055	4th	0.383	4th
H_2	0.148	2nd	0.751	2nd
FLY	0.167	1st	0.757	1st
SUPERC	0.103	3rd	0.528	3rd
LITH	0.164	1st	0.756	1st
NaS	0.151	2nd	0.751	2nd
VRB	0.156	2nd	0.751	2nd

2.3 *Multi-criteria analysis in the renewable energy industry* by J. R. S. C. Mateo

Mateo asserts that the necessity for a well-developed MCDA method stems from two main reasons. The first is the need to take in to account the interests and preferences of those actors (individuals/ institutions/ potential investors/ governments etc.) that may be affected by the energy planning. Each of these actors brings their own criteria and point of view to the decision problem and must be heard. The second reason is the change from an almost singular concern with single bottom line (profit-centric) to an environment with mounting pressures to adhere to triple bottom line standards, this involves remaining competitive and profitable but also acting socially and environmentally responsibly. The criteria that affect the chance of success of renewable energy projects are therefore typically broken down in to 4 categories; economic, social, environmental and technical.

The usefulness of different models is then assessed, it is stated that the methods and results are not all necessarily comparable; this primarily due to model assumptions which should be considered when the model is selected. Mateo asserts that inconsistencies may arise from several sources;

i) The choice problem formulation do not reflect the same preference structures,
ii) The way in which preference information is processed varies between different methods, and
iii) The methods interpret the criterion weights differently.

A defined list of steps is then presented that illustrates how to correctly construct a decision model. The steps are;

1- Define the problem, generate alternatives, establish criteria,
2- Assign weights to each of the criteria,
3- Construct the evaluation matrices,
4- Select appropriate MCDA method and apply it, and
5- Rank the alternatives.

Assessing these steps against the method that Barin et al. (June 2011) used in order to carry out the AHP approach and fuzzy multi-sets and multi-rules validates two points; i) that Barin et al. approached their problem in an appropriate manner and worked through to a solution correctly (there is now more confidence that following their procedure will be helpful), and ii) that the steps laid out above work functionally well in helping to reach a solution.

Eleven MCDA methods were assessed in detail, their strengths and weaknesses noted and their applicability to various types of problems was noted. Brief positives/negatives summaries of AHP and PROMETHEE are provided (all methods were assessed, the 2 shown were the most appropriate and so are shown).

AHP

Pro's; deals with qualitative criteria, handles large quantities of criteria well, handles criteria where specific characteristics are not well known, allows for (expert) opinions on intangible aspects, easy to use.

Con's; criticized for inability to adequately accommodate for the inherent uncertainty and imprecision associated with certain environments, difficult to accurately scale specific quantitative criteria for pairwise comparison.

PROMETHEE

Pro's; has multiple ranking formats to allow for increased accuracy, utilises outranking methodology in a format that decreases complexity, well suited to problems where a finite number of alternatives are to be ranked against several criteria, user friendly software available to apply process.

Con's; process can be hard to understand if unfamiliar which may lead to the black box effect described by Løken (2007), care must be taken to ensure meaningful differences between evaluations of criteria.

As Løken (2007) explained, the ability of the DM to understand what is happening within the process is important if they are to trust the resultant recommendations. From Mateo's work it is apparent that PROMETHEE, while very applicable to this multi-criteria problem type, has a process that is intricate and hard to follow without technical knowledge. As can been seen in the Barin et al. (June 2011) paper, the results from AHP are easily understood and the process to reach these results is simple to follow and understand. These have both been identified as important aspects of the model that is being used to deal with the mine site energy storage decision problem, and so it can be concluded that AHP is a more appropriate method to use. The added support of a fully worked AHP approach by Barin et al. (June 2011), and a defined method to help with constructing a decision model by Mateo (2012), will assist with ensuring the correct application of the AHP method.

3. METHOD

The following is provided so that the validity of the process that has been produced can be judged. All the steps that were undertaken, as well as the backing rationale for the design characteristics, are provided.

3.1 PROCESS

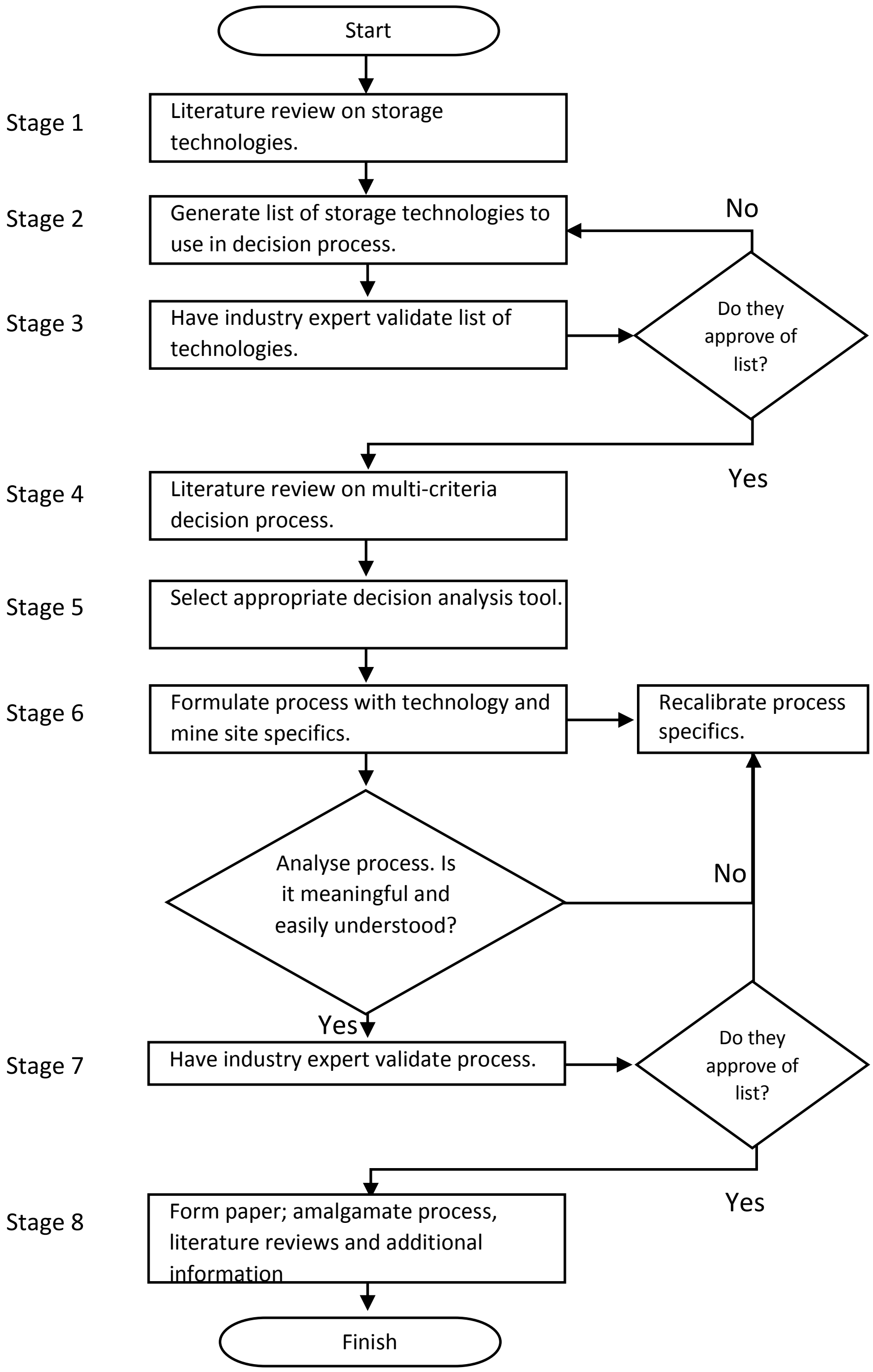


Figure 3 - Process map of Creating a Decision Analysis Process

Step 1 – Storage Technologies Literature Review

Review of current energy storage methods that are available. Only high quality, peer reviewed primary, secondary and tertiary sources are used. Starting with the Large Energy Storage Systems Handbook by Barnes and Levine (2011), the initial group of storage technologies to include in the alternatives list was made; this provided the starting point from where further research could take place. By searching each technology individually, and following any referenced material downstream, it was possible to locate more up to date material regarding breaking technology and research. After enough material was covered it became apparent that, excluding experimental technology, a list had been compiled (a select group from this list can be seen in tables in section 4).

Step 2 – Generate a list of technologies to use in the decision process

At this stage it is necessary to generate a list of criteria that each technology must meet in order to be viable for use on a mine site. These criteria are not necessarily those that will be used in the decision process itself, but are a means of reducing the larger technology space down to a more meaningful subgroup. Two groups of criteria are identified; a primary (elimination) group used in the screening stage, and a secondary (selection) group used in the decision stage (these are further explained in Section 4.1.2). The storage technology space is assessed against the primary criteria, any that do not meet these are omitted from the later stages of the process. Examples of omissions are the Flywheel and Super Capacitor storage mediums for having an output duration on the order of seconds, this is unsuitable for mine site full load power supply applications.

Step 3 – validation by industry expert

Now that a select list of possible alternatives has been identified, outside evaluation is necessary to ensure process integrity. To increase the reliability of the process, utilising multiple experts is advised as it is then possible to contrast judgements and opinions until a consensus is reached. In this instance only a single expert was asked to validate the energy storage list, a greater amount of corroboration would have been preferred.

Step 4 – Multiple-Criteria Decision Processes Literature Review

This is a review of MCDP's, starting with the entire spectrum of models. By beginning at a general and broad level, it allows the review to encompass all possibilities and eliminate those which appear not to be useful. In this case that meant starting with Multi-criteria Decision Analysis :

Methods and Software by Ishizaka and Nemery (2013) and Use of Multi-criteria Decision Analysis Methods for Energy Planning Problems by Løken (2007); these provided useful insight in to the MCDP's as a whole, and some direction as to what processes would be useful within the broad subcategories that were identified in the papers. An investigation in to the applicability of various methods was carried out until a reduced list of possible processes was established. This reduced list was then contrasted to those processes used within other papers that focused on similar problems, the primary comparison being with Multiple Criteria Analysis for Energy Storage Selection by Barin et al. (June 2011). This resulted in 2 processes being favoured for use in the selection process.

<u>Step 5 – Select appropriate decision analysis model</u>

Following the MCDP literary review, there should be a choice between a limited number of models; in this instance it is between AHP and Fuzzy multi-sets and multi-rules. Considering that Barin et al. (June 2011) utilised both methods in their paper and settled with the same results, it is possible to conclude that either method will suffice as the alternatives and selection criteria will be similar. With this knowledge, the AHP model was selected (again Fuzzy multi-sets and multi-rules would provide the same results but the process is less comprehensible, which goes against the aims of the decision process).

<u>Step 6 – Formulate selection process with technology and mine site specifics</u>

By combining the finalised list of alternative storage methods with the criteria that they will be assessed against, and the MCDP method that was selected, it is possible to simulate the energy storage decision process. Utilising the AHP method, it is first necessary to rate each alternative against each criteria (this is shown in Section 4.1.2; Table 7 to Table 10); this can be split up in to binary characteristics (e.g. does an alternative allow for load levelling? yes/no) and value based data (e.g. efficiency). Once this is done, a pairwise comparison is carried out between the criterion, and also the alternatives, to produce Pairwise Comparison Matrices (PCM's). Each PCM results in a Relative Weighting for each criterion and alternative, the Relative Weights from each table are then multiplied together. By summing these multiplications we are left with the Final Relative Weights, which are the values used to rank the alternatives with the criteria.

When using AHP the Consistency Ratio (CR) must be used to ensure reliability of the relationship between values and judgements; CR essentially rejects any incorrect prioritising of one alternative over another, or criteria over another, if it is inconsistent with other priorities. When using a program to carry out the pairwise comparisons, the CR is automatically calculated ensuring the reliability of the results.

To generate the Decision Tree model the criteria from the AHP model should be used, this ensures comparability between the solutions from the AHP process and the Decision Tree process. These criteria must be further defined in to several ranges (an example is illustrated in Table 11), these ranges need to allow for the differentiation between storage methods (for example, power requirement ranges of <15MW, 15-40MW and >40MW means that any storage method that is inspected will be sorted in to 1 of these 3 ranges). All the combinations of the criteria must be inspected and the appropriate storage methods noted for each (an example is shown in Table 12); any possible minimisation of repeated solution sets should be carried out here to ensure the simplest form of the decision tree is realised. This information can then transferred to a diagrammatic representation, as shown in Figure 6 - Reduced Decision Tree.

<u>Step 7 - validation by industry expert</u>

Again it is necessary to have the work validated by industry experts to ensure reliability of the results. This time it is the process itself that requires corroboration, with checking of weightings and input data to be prioritised.

<u>Step 8 – Amalgamate information to form paper</u>

To enable further use of, and expansion to, the process created, all information pertaining to the research, planning, creating and testing of the decision process should be recorded. That is the purpose of this paper.

4. RESULTS

4.1 DECISION PROCESS

In order to provide an easily accessible energy storage decision process to those in the mining industry, which Løken (2007) asserted was an important aspect of a decision model for DM's, there has been generated a series of AHP recommendations under different scenarios, as well as a decision tree model.

The AHP recommendations will allow those in the mining industry to ascertain which solution may be appropriate with limited information; all they may need to know initially is that space restriction is their key concern, or that the expected lifetime of the operation is only 15years. There have been 4 different scenarios worked through to solution; 1) Power output is a priority, 2) Maximum lifespan of equipment is a priority, 3) Space restriction is a priority, and 4) Temperature range on site is a priority. The illustrated example that follows is for scenario 1) Power output is a priority, this places a heavier weighting on the Power output criteria.

As well as this, a decision tree with multiple choice branches has been implemented so that, if the industry personnel knows additional information regarding the criterion in question, they will be able to receive a more tailored solution and make a more informed decision.

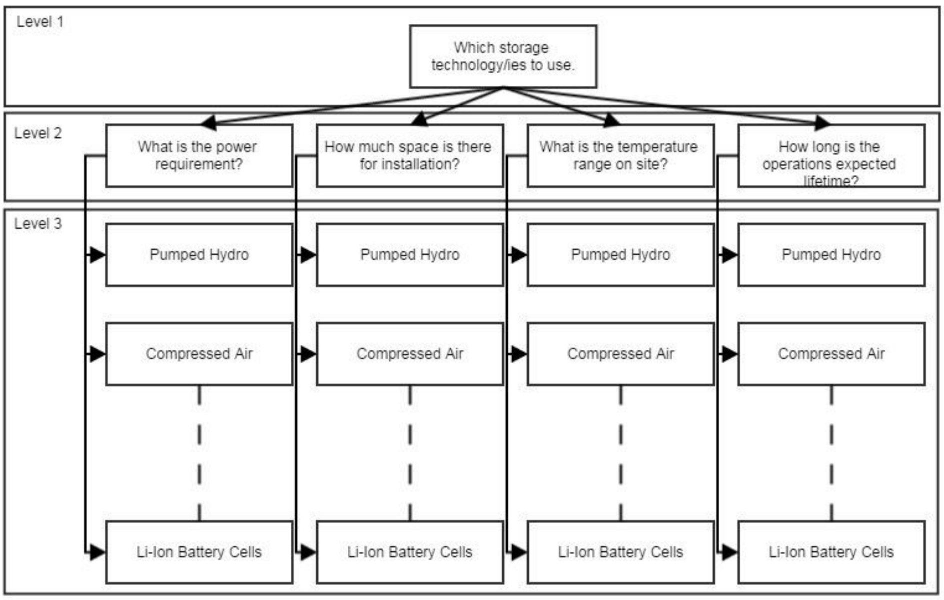


Figure 4 - AHP hierarchy

4.1.1 Alternatives Classification

For an entire description of the characteristics and attributes of each of the alternatives, both those that made it to the final stages of the decision process and those that did not, please refer to section 8.2 - Appendix 2: Current Storage Environment where there is a detailed list. What follows directly is an abstract of that.

The following list details the storage systems that are capable of being used for mine site storage purposes;

CES	Cryogenic Energy Storage
H_2	Hydrogen Energy Storage
PHES	Pumped Hydro Energy Storage
CAES	Compressed Air Energy Storage
TPHE	Thermal Pumped Heat Electrical
TCSE	Thermal Concentrating Solar Energy
ALA	Advanced Lead Acid Batteries
ZHC	Zinc Hybrid Cathode Batteries
AHI	Aqueous Hydrogen Ion Batteries
LIO	Lithium Ion Batteries

4.1.2 Criteria Classification

The criterion have been compared in a pairwise fashion according to the rating scale recommended by Saaty and Vargas (2012) shown in Table 4. These weightings have then been applied to each of the following Pairwise Comparison Matrices in order to ascertain the Final Real Weightings. Table 3 below shows a pairwise comparison between the following criteria;

PO — Power Output characteristics; includes maximum possible instantaneous output and maximum duration of output, as both are important for providing baseload; greater output and duration values result in higher ranking.

SP — Space for installation; evaluates the storage methods spatial requirements for installation; less space required results in higher ranking. Ability to be

	modularised is included as this makes tailoring to specific situations more simple.
TR	Temperature Range of optimal operation; assesses the temperature ranges in which the storage method can operate optimally; larger ranges result in higher ranking.
EL	Expected Lifetime of operation; evaluates the expected duration of the storage method; greater longevity of the method results in higher ranking.

Table 3 - PCM of Selection Criteria

Criteria	PO	SP	TR	EL
PO	1	5	5	5
SP	1/5	1	1	1
TR	1/5	1	1	1
EL	1/5	1	1	1

The weight given to the priority criteria is selected at an intensity of importance of five, this corresponds to strong importance. This weighting will result in the priority criteria having a much stronger influence on the final real weighting than the remaining three criteria, which all have an intensity of importance of 1, corresponding to equal importance (the levels of intensity of importance and their definitions are shown in Table 4).

Table 4 – PCM Weight Classification

(Saaty and Vargas, 2012)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

<u>Cost</u>

The economic justification for storage systems necessarily requires that the annualized capital (initial capital spread over the expected lifetime of the operation) and operating costs be less than those of the primary generating equipment (such as diesel generators) that they would replace. In general, energy storage systems accrue fuel cost savings when compared with primary equipment, often at an initial capital cost premium (Dincer, 2010). Due to the profitand-loss-centric nature of the mining industry, cost was selected as a pre-screening variable. It was looked at on both a $/kW and $/kWh basis and compared to the market rates for grid-power or primary generating equipment supplied power, which can have a levelised price anywhere from $0.08-$0.4/kWh (Harries, 2014). This variable was used to eliminate any technologies that did not show themselves to be competitive with primary power sources, and so those technologies were omitted from the selection process. Table 5 below shows a list of the technologies that were researched and those that were deemed inappropriate for mine site applications. It shows the storage method in the left hand column, and its corresponding costs on a dollar per kilowatt and dollar per kilowatt hour basis in the centre and right hand columns. Note the large cost for storage ($/kWh) associated with superconducting magnetic energy storage in comparison to pumped hydro, this is one factor that differentiates viable methods from unviable.

Table 5 - cost of storage in $/kW and $/kWh

(Deane et al., 2010, Chen et al., 2009, Bhuiyan and Yazdani, 2012, Yang et al., 2011, Whitacre, 2014, T.Kousksou et al., 2013)

Storage Method		**$/kW**	**$/kWh**
~~SMES~~		~~≈ 300~~	~~> 20,000~~
~~Flywheel~~		~~500-10k~~	~~1k-5k~~
~~Super Capacitors~~		~~300~~	~~2000~~
Cryogenic Energy Storage (CES)		200-300	3-30
Hydrogen		D	D
PHES		690-1800	15 - 150
CAES		400 - 1000	10 - 100
Thermal	PHE	≈ 470	≈ 17
	CSE	1k – 6k	N/A
Electrochemical	Adv. Lead Acid	200-1k	< 400
	Zinc Hybrid Cathode Battery	N/A	160
	Aqueous Hydrogen Ion Battery	N/A	< 200
	Lithium Ion Battery	1.5k-4k	800-4k

N/A – Not Available or could not find a reputable source

D – Dependent on hydrogen production method, more information available in Appendix 8.2.5 - Hydrogen

Power Output Capacity

The capacity of each option is a defining factor on two fronts; its ability to output enough instantaneous power to allow full site operation, and its ability to output an average level of power for an extended period of time so as to allow for the possibility of energy generation downtime. This factor played a role at both the primary and secondary level; if the maximum output or duration of output was not adequate the technology was omitted from the process. If it was adequate then the level of output and possible durations of output were compared to each other. Below are the capacity and output characteristics of the various technologies, those that were discounted due to inadequacy are marked as such.

Table 6 - Storage Capacity in kW/MW/GW

(Ter-Gazarian, 1994, Voith, 2014, Wood, 2013, Whitacre, 2014, Barnes and Levine, 2011, T.Kousksou et al., 2013, Chen et al., 2009)

Storage Method		Power Output	Duration of Output
~~SMES~~		~~100kW – 10 MW~~	~~Several seconds~~
~~Flywheel~~		~~250kW~~	~~<1 hour~~
~~Super Capacitors~~		~~300kW~~	~~<several minutes~~
Cryogenic Energy Storage (CES)		100kw – 300MW	>24 hours
Hydrogen		100kW – 300MW	>24 hours
PHES		100MW to 1GW+	>24 hours
CAES		100MW to 1GW+	>24 hours
Thermal	PHE	2-5MW per unit, grouping can achieve GW scale.	>24 hours
	CSE	<50MW	<18 hours
Electrochemical	Adv. Lead Acid	< 40MW	4-8 hours
	Zinc Hybrid Cathode Battery	<40MW	4-12 hours
	Aqueous Hydrogen Ion Battery	< 40MW	12 hours
	Lithium Ion Battery	< 40MW	4-8 hours

Below is the weighting of each alternative in regards to its Power Output (PO) capabilities. This table is used during the AHP process to determine the optimal solution.

Table 7 - PCM for Power Output characteristics (PO)

PO	CES	H2	PHES	CAES	TPHE	TCSE	ALA	ZHC	AHI	L-Ion
CES	1	1/6	1/6	1/6	1/6	1	2	2	2	2
H2	6	1	1	1	1	6	8	8	8	8
PHES	6	1	1	1	1	6	8	8	8	8
CAES	6	1	1	1	1	6	8	8	8	8
TPHE	6	1	1	1	1	6	8	8	8	8
TCSE	1	1/6	1/6	1/6	1/6	1	3	3	3	3
ALA	1/2	1/8	1/8	1/8	1/8	1/3	1	1	1	1
ZHC	1/2	1/8	1/8	1/8	1/8	1/3	1	1	1	1
AHI	1/2	1/8	1/8	1/8	1/8	1/3	1	1	1	1
L-Ion	1/2	1/8	1/8	1/8	1/8	1/3	1	1	1	1

Installation Size

A concern for mine sites (and remote communities) is the amount of space that an energy storage solution will occupy, though this is always on a situational basis. Reasons ranging from visual pollution objections as a result of large compound installations to physical limitations of the property, which can be imposed by local councils or geographical location, can cause this to be a defining factor. As such this plays a secondary role in the selection process, where it is broken in to “Restricted Space” and “Unrestricted Space”.

Below is the weighting of each alternative in regards to its Space Requirements (SP).

Table 8 - PCM for Space Requirements

SP	CES	H2	PHES	CAES	TPHE	TCSE	ALA	ZHC	AHI	L-Ion
CES	1	3	6	4	1	6	1	1	1	1
H2	1/3	1	2	1	1/3	2	1/3	1/3	1/3	1/3
PHES	1/6	1/2	1	1/2	1/6	1	1/6	1/6	1/6	1/6
CAES	1/4	1	2	1	1/4	2	1/5	1/5	1/5	1/5
TPHE	1	3	6	4	1	6	1	1	1	1
TCSE	1/6	1/2	1	1/2	1/6	1	1/6	1/6	1/6	1/6
ALA	1	3	6	5	1	6	1	1	1	1
ZHC	1	3	6	5	1	6	1	1	1	1
AHI	1	3	6	5	1	6	1	1	1	1
L-Ion	1	3	6	5	1	6	1	1	1	1

Site Temperature

For the majority of battery technologies, temperature plays a role in their operating efficiency. Being too cool increases their internal resistance, and too hot can result in a net loss of capacity (Linden and Reddy, 2002). This results in their application needing additional cooling or other maintenance requirements in some circumstances, which may result in another technology being more appealing. The temperature ranges were specified at the boundaries of efficient operation of the technologies that are effected by temperatures, allowing them to be easily differentiated by this criteria.

Below is the weighting of each alternative in regards to its Temperature Range (TR) requirements.

Table 9 - PCM for Temperature Range Requirements

TR	CES	H2	PHES	CAES	TPHE	TCSE	ALA	ZHC	AHI	L-Ion
CES	1	1	3	1	3	3	6	4	7	3
H2	1	1	3	1	4	4	6	4	7	6
PHES	1/3	1/3	1	1/3	1	1	4	3	4	1
CAES	1	1	3	1	4	4	6	4	7	3
TPHE	1/3	1/4	1	1/4	1	1	3	2	4	1
TCSE	1/3	1/4	1	1/4	1	1	3	2	4	1
ALA	1/6	1/6	1/4	1/6	1/3	1/3	1	1/3	1/2	1/3
ZHC	1/4	1/4	1/3	1/4	1/2	1/2	3	1	3	1/2
AHI	1/7	1/7	1/4	1/7	1/4	1/4	2	1/3	1	1/4
L-Ion	3	1/6	1	1/3	1	1	3	2	4	1

Expected Operational Life Span

Depending on the length of time the operation will continue, the appropriate technology must be selected so that it will confidently last at least as long. The criteria has again been specified at the boundaries of the technologies endurance, so as to aptly differentiate between them.

Below is the weighting of each alternative in regards to its Expected Lifetime (EL). This table is used during the AHP process to determine the optimal solution.

Table 10 - PCM for Expected Lifetime of Equipment

EL	CES	H2	PHES	CAES	TPHE	TCSE	ALA	ZHC	AHI	L-Ion
CES	1	1	1	1	1	4	7	4	7	4
H2	1	1	1	1	1	4	7	4	7	4
PHES	1	1	1	1	1	4	7	4	7	4
CAES	1	1	1	1	1	4	7	4	7	4
TPHE	1	1	1	1	1	4	7	4	7	4
TCSE	1/4	1/4	1/4	1/4	1/4	1	5	1	5	1
ALA	1/7	1/7	1/7	1/7	1/7	1/5	1	1/5	1	1/5
ZHC	1/4	1/4	1/4	1/4	1/4	1	5	1	5	1
AHI	1/7	1/7	1/7	1/7	1/7	1/5	1	1/5	1	1/5
L-Ion	1/4	1/4	1/4	1/4	1/4	1	5	1	5	1

The program that was utilised to combine Table 3 with Table 7, and in turn produce the following graph, was MakeItRational (accessed at https://makeitrational.com/demo/decision-making-software); this program was recommended by Ishizaka and Nemery (2013). The program ensures that there are no inconsistencies between the weightings, so that the Consistency Ratio is within acceptable limits.

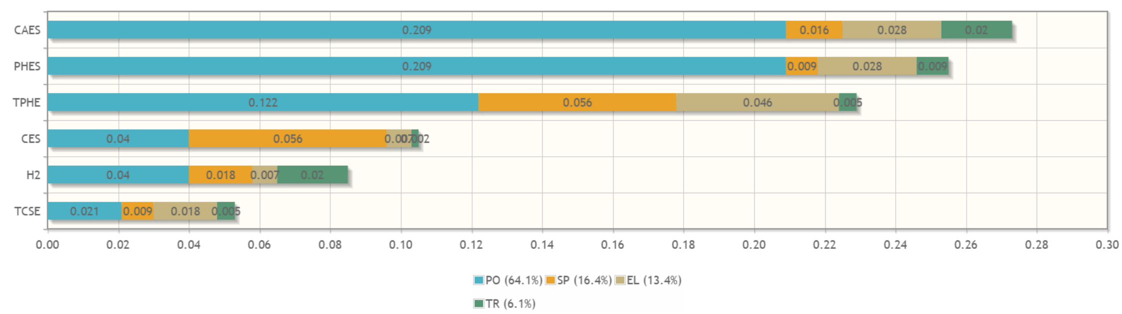


Figure 5 - Final Real Weighting, with Power Output Priority

(A full-size version is provided in Appendix 1: Analytical Hierarchy Process Recommendations, along with the remaining 3 recommendations)

Figure 5 illustrates how well each alternative performs under each criteria. Taking the top bar, which represents Compressed Air Energy Storage (CAES), as an example; the blue section denotes the relative Power Output (PO) performance of CAES against the other alternatives. Similarly, the orange section represents Space Requirements (SP) in comparison to the other alternatives. From Figure 5 we can see that CAES has the equal best PO performance along with pumped hydro (PHES), and the fourth best SP performance. The final ranking of the alternatives is; 1st CAES, 2nd PHES, 3rd TPHE, 4th CES, 5th H_2, 6th TCSE. It is also easy to note that the Power Output characteristics criterion makes up a significant portion of the total final weighting for CAES, PHES and TPHE which is to be expected; all 3 of these methods have large energy storage capacities (ranging in to the GW+) and can output instantaneous power in the MW range for extended periods of time (TPHE at lower levels than the prior 2). Similar results can be seen for the remaining 3 scenarios in Appendix 1: Analytical Hierarchy Process Recommendations.

4.2 Decision Tree Diagram

In order to create the decision tree diagram, no strict methodology was utilised. To begin with, ranges were specified for each of the criteria that were utilised in the AHP method. The same criteria were used so as to maintain similarity and comparability between the AHP solutions and the Decision Tree solutions. In the example shown in Table 11 below, 3 power output ranges are selected; less than 15MW, 15 to 40MW, and greater than 40MW. Amount of space for installation has been divided in to Restricted and Unrestricted. The operating temperature ranges are selected as -30°C to 50°C, -10°C to 40°C and 0°C to 55°C. The expected lifetime ranges are less than 11 years, 11 to 20 years and greater than 20 years.

Table 11 - Ranges for Criteria along with letter assignment

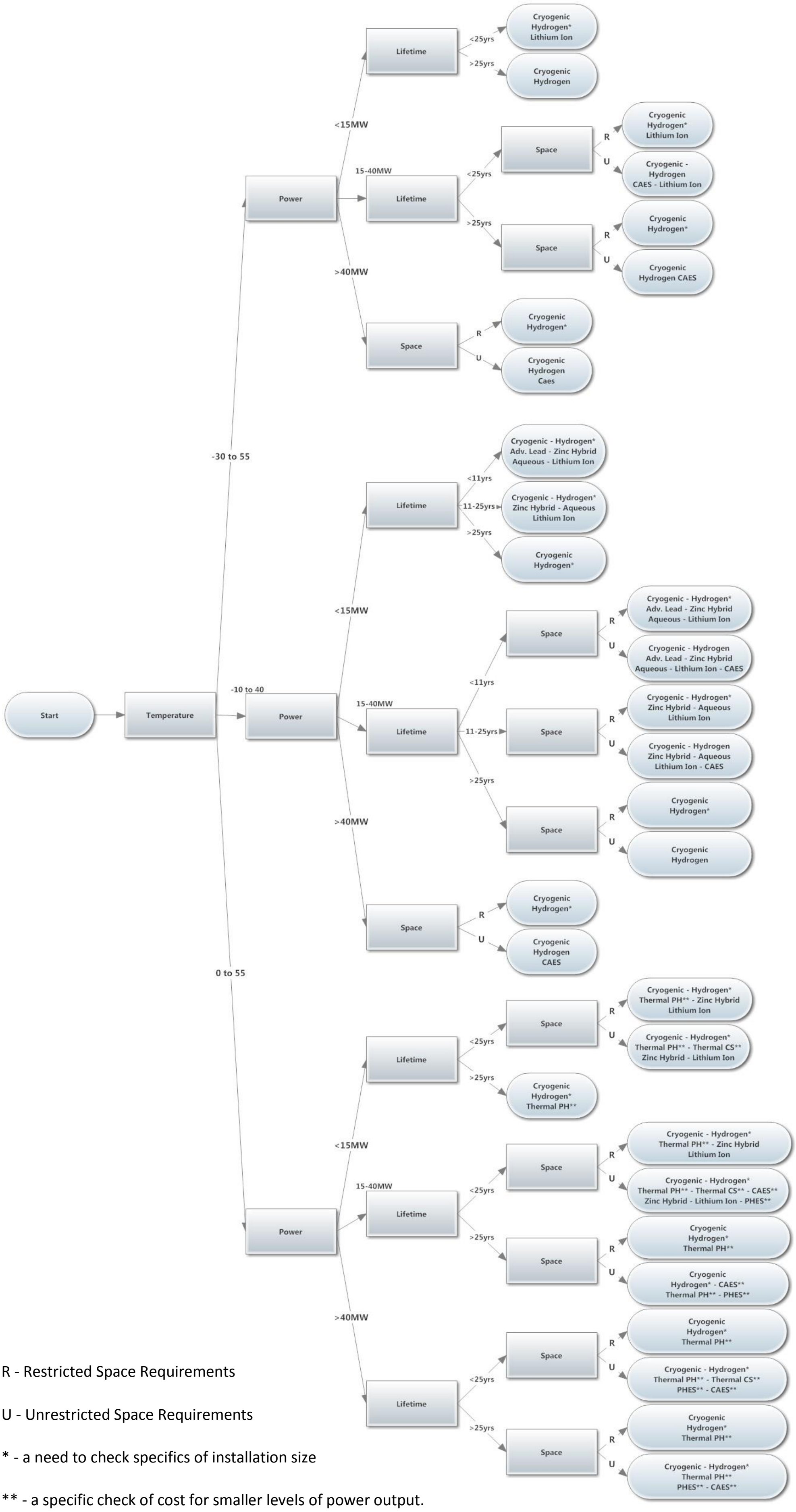
What is the power requirement? (PO)		Space for Installation? (SP)		What is the temperature range on site (°C)? (TR)		How long is the expected lifetime of the operation? (EL)	
A	<15MW	A	Restricted space	A	-30 to 55	A	<11 years
B	15-40MW	B	Unrestricted	B	-10 to 40	B	11-20 years
C	>40MW			C	0 to 55	C	>20 years

From here a list of all possible combinations of the 4 criteria was assembled, so as to form a Boolean style list; the first third of this list is displayed in Table 12. All the alternatives that were a solution for the specific Boolean combinations were added to this list. For example, the first entry in Table 12 refers to the following requirements; <15MW, Restricted space, -30°C to 50°C and <11 years, for this combination only Lithium batteries can be used as a solution (this is merely an example, other solutions exist).

Table 12 - Example section of criterion Boolean table

aaaa	Lithium	**abaa**	Lithium/ Thermal
aaab	Lithium	**abab**	Lithium
aaac	Lithium	**abac**	Lithium
aaba	Lithium/ Adv Lead Acid	**abba**	Lithium/ Adv Lead Acid/ Thermal
aabb	Lithium	**abbb**	Lithium
aabc	Lithium	**abbc**	Lithium
aaca	Lithium/ Adv Lead Acid/ Aquion	**abca**	Lithium/ Adv Lead Acid/ Aquion/ Thermal
aacb	Lithium/ Aquion (15.4 years)	**abcb**	Lithium/ Aquion (15.4 years)
aacc	Lithium	**abcc**	Lithium
aada	Lithium/ Adv Lead Acid/ Aquion	**abda**	Lithium/ Thermal
aadb	Lithium/ Aquion (15.4 years)	**abdb**	Lithium
aadc	Lithium	**abdc**	Lithium

Once this was finished and a complete set had been realised, a minimisation approach was taken to find redundant states and remove them. This was carried out after the initial non-reduced decision tree was drawn up, the result having far too many branches and repetition of possible solutions. This last stage was recursively carried out until an acceptable, but information lossless, process tree was realised; this is displayed in Figure 6 - Reduced Decision Tree.



R - Restricted Space Requirements

U - Unrestricted Space Requirements

* - a need to check specifics of installation size

** - a specific check of cost for smaller levels of power output.

Figure 6 - Reduced Decision Tree

5. Discussion

From the list of alternatives, all are in stages of technical maturity except for Aqueous Hydrogen Ion Batteries and Zinc Hybrid Cathode Batteries. This is not to say that there are not still advances to be made with efficiencies, installation costs and so on with other methods, they are simply able to be deployed with confidence in their operation capabilities. Aqueous Hydrogen Ion Batteries and Zinc Hybrid Cathode Batteries are both in their infancy, with laboratory tests and the beginning stages of field testing being carried out, and so their deployment immediately (as of the submission of this paper) is not advised.

5.1 Difficulties with Technology Adoption

It is necessary to look at the impact that current operating processes have had on generating barriers to entry for the adoption of new technologies. There are 3 scenarios in which renewable energy sources and energy storage infrastructure could be taken up;

1) It could be adopted by an established company at an established mine site. Such a company would already have contracts and relationships with suppliers, maintenance contractors and many other personnel associated with their method of power generation. At an established site they would also have fully implemented infrastructure, backup equipment and maintenance supplies to use for repairs.
2) An established company at a new mine site could implement it. This company would have the same personnel barriers with whom they have formed a relationship or have a contract. In place of previously implemented infrastructure the challenge would be utilising a new technology and a new location, and all of the potential teething problems that go hand-in-hand with that.
3) It could be implemented by a new company at a new mine site. This would have the fewest barriers to entry as there would be no existing contracts or relationships with suppliers or other stakeholders, and no infrastructure in place to act as an adoption-deterrent. There would be very large organisational teething issues with the company itself, which may negatively skew their perspective of adopting a new technology at the same time.

As has been noted, the majority of mine site power production is via fossil fuel based processes, especially diesel. From the above 3 points, it is difficult to get non-diesel power generation technologies in to the mining industry due to the well-established, and tried and tested infrastructure. Diesel is used for operating trucks and machinery as well and, to solve this problem in the long term, it would be necessary to replace this machinery with electric equivalents (Harries, 2014).

Gordon (2013) asserts that one possible solution that could help to phase-out diesel and usher in RES is the use of hybrid systems. Hybrid systems involve control systems that utilise mechanisms to swap between diesel and renewable/ stored energy in order to produce constant power. This results in a reduction of the total required storage capacity for renewables which consequentially leads to a reduction of storage costs, making RES much more competitive. This implementation can also reduce diesel consumption by up to 35% which could have the effect of shrinking diesel reliance and infrastructure, making renewables even more feasible (Harries, 2014).

6. Conclusion and Future Work

This paper explores models that can be used to evaluate problems that must consider multiple criteria and multiple alternatives, these models are categorised into the Multiple Criteria Decision Analysis grouping. Several of these models were identified that appeared promising, and AHP was selected to be used as the foundation for the energy storage decision process. Four criteria were defined within this model; 1) Power Output characteristics, 2) Space Requirements, 3) Operational Temperature Range, and 4) Expected Lifetime. The criteria were then used to assess ten storage methods to judge the level of appropriateness of each under four different circumstances. These circumstances were 1) Power Output priority, 2) Space Requirement priority, 3) Operational Temperature Range priority, and 4) Expected Lifetime priority (i.e. each simulation made a single criteria the priority). For each scenario a ranked list of energy storage solutions was generated, providing a recommendation of which method was most appropriate.

A decision tree was also created, using the criteria and alternatives selected for the AHP process but further specifying ranges on the criteria; a four tiered tree was generated. The use of ranges with the criteria allows for additional specificity from the Decision Maker (DM), in turn allowing a more tailored and populated subset of possible energy storage solutions. The decision tree provides a way of making a decision without having to rework criteria pairwise comparisons or alternative weightings in order to reach a recommendation, saving time and reducing complexity.

The paper has a number of specific objectives (identified in section 1.3 - Objectives), the outcomes for each are discussed below.

1. *Assess available energy storage methods to identify the current state of technologies and pending research into improvements, with special attention paid to those that are applicable to mine sites.*

   A literature review was undertaken to explore information regarding cost of installation and operation, spatial requirements for installation, acceptable temperatures that the storage equipment can operate in, expected lifetime of the storage method, level of technical maturity and efficiency levels. This information was studied for different forms of energy storage, and used to determine which storage methods were appropriate for mine site use. The result is a list of ten alternatives that is shown in section 4.1.1 - Alternatives Classification, all of which can be deployed for use on a mine site.

2. *Explore current Multiple Criteria Decision Models (MCDM). Analyse any specific applications of these models to the selection of storage technologies for mine sites or related scenarios. Identify an appropriate MCDM that can be used to reach a recommendation for the energy storage decision problem.*

   A literature review was carried out and an MCDA model was selected. The characteristics of different types of MCDA methods were assessed to determine their applicability to this decision problem. Characteristics such as their ability to handle a large number of qualitative and quantitative criteria, make use of a process that is relatively easy to understand, and to generate comprehensible recommendations were all investigated. AHP, PROMETHEE and fuzzy multi-sets and multi-rules were all found to be applicable methods. When considering the requirements of this problem, the desire for a process that is easily understood, AHP was selected as the method to continue with as it was the most graspable.

3. *Develop a non-technical decision process for people in the mining industry. It should ascertain the most appropriate energy storage solution for a chosen mine site, this includes; a) Identify which technologies are acceptable for forming part, or all, of a solution, and b) Analyse criteria against which possible technologies can be assessed, depending on mine site requirements*

   An AHP based decision process was created. It incorporated a refined list of storage method alternatives that were applicable to remote mine sites. Four criteria were specified and were used to assess the applicability of the alternatives under four different scenarios. As a result four specific recommendations are provided by this process. A decision tree was also developed to provide additional specificity in the case that the AHP process was too generalised, as described earlier. The combination of the 2 decision processes fulfils the requirements of being an easy-to-utilise process that provides meaningful recommendations, and enables those within the mining industry to carry out initial energy storage investigations more simply.

   It would be useful to employ either PROMETHEE or fuzzy multi-sets and multi-rules with the same set of criteria and alternatives, and generate recommendations, in order to further validate those recommendations proffered by the AHP process. Barin et al. (June 2011) puts to use both AHP and fuzzy multi-sets and multi-rules and reaches the same conclusion via these processes. This suggests the same would occur here, under the energy storage decision problem conditions, but this may not be the case; individual assessment should still be carried out.

4. *Critically assess and review results and identify areas of further research.*

The completed decision processes and resulting recommendations were assessed against other similar theoretical models and frameworks, such as those described by Barin et al. (June 2011), Løken (2007) and Mateo (2012), so that the model building process and the resultant decision processes could be validated; upon inspection they are both acceptable. It could be beneficial to recalibrate the AHP process with the inclusion of additional criteria (for example. a minimum investment amount, level of relative safety and environmental impacts could all be included) so as to make the recommendations more informative.

Some areas that have been identified as requiring work are as follows;

i) Additional industry expert corroboration throughout the design of the decision process. The utilisation of the Delphi method is recommended in order to communication with a large panel of experts to recursively expand and refine the list of alternatives, selection criteria, criteria ranges and the resultant decision models.

ii) Example mine sites need to be used to assess the usefulness of the decision model. Mine sites that have already deployed renewable energy sources and storage methods, and that have released the appropriate information so that the decision model can be used, should be evaluated to see if the model recommendations match what has physically been installed. This will illustrate whether the model reflects real industry standards, and if not can be adjusted to do so.

iii) A cost analysis for the above example mine sites, focusing on the differences in provision of power via connection to a grid versus primary power units (such as diesel generators) versus renewable energy generation and storage. This should be carried out for each recommendation.

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8. APPENDICES

8.1 APPENDIX 1: ANALYTICAL HIERARCHY PROCESS RECOMMENDATIONS

1-1: AHP Final Real Weighting, Power Output Priority

1-2: AHP Final Real Weighting, Space Requirement Priority

1-3: AHP Final Real Weighting, Operational Temperature Priority

1-4: AHP Final Real Weighting, Lifetime of Storage Priority

8.1.1 Appendix 1-1: AHP Final Real Weighting, Power Output Priority

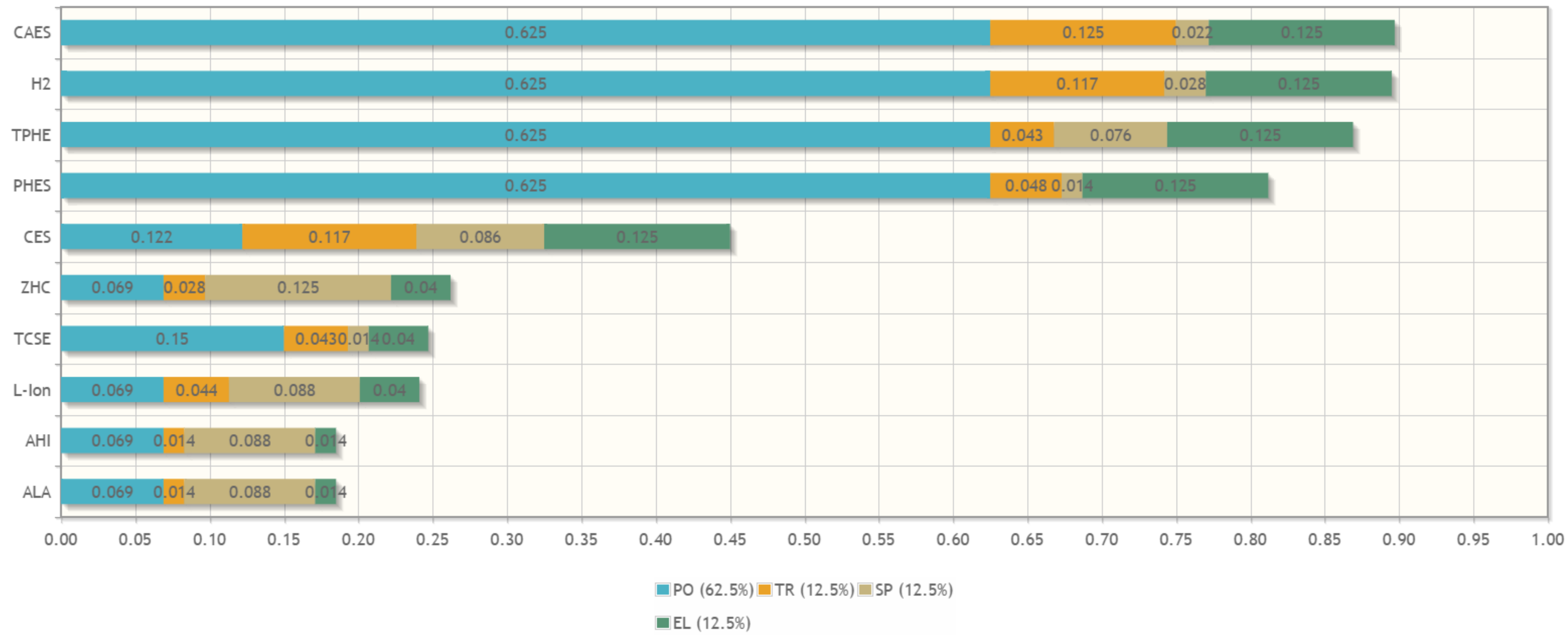

Figure 7 - AHP Final Real Weighting, Power Output Priority

(PO – Power Output Characteristics, TR – Operational Temperature Range, SP – Space Requirements, EL – Expected Lifetime of Operation)

8.1.2 Appendix 1-2: AHP Final Real Weighting, Space Requirement Priority

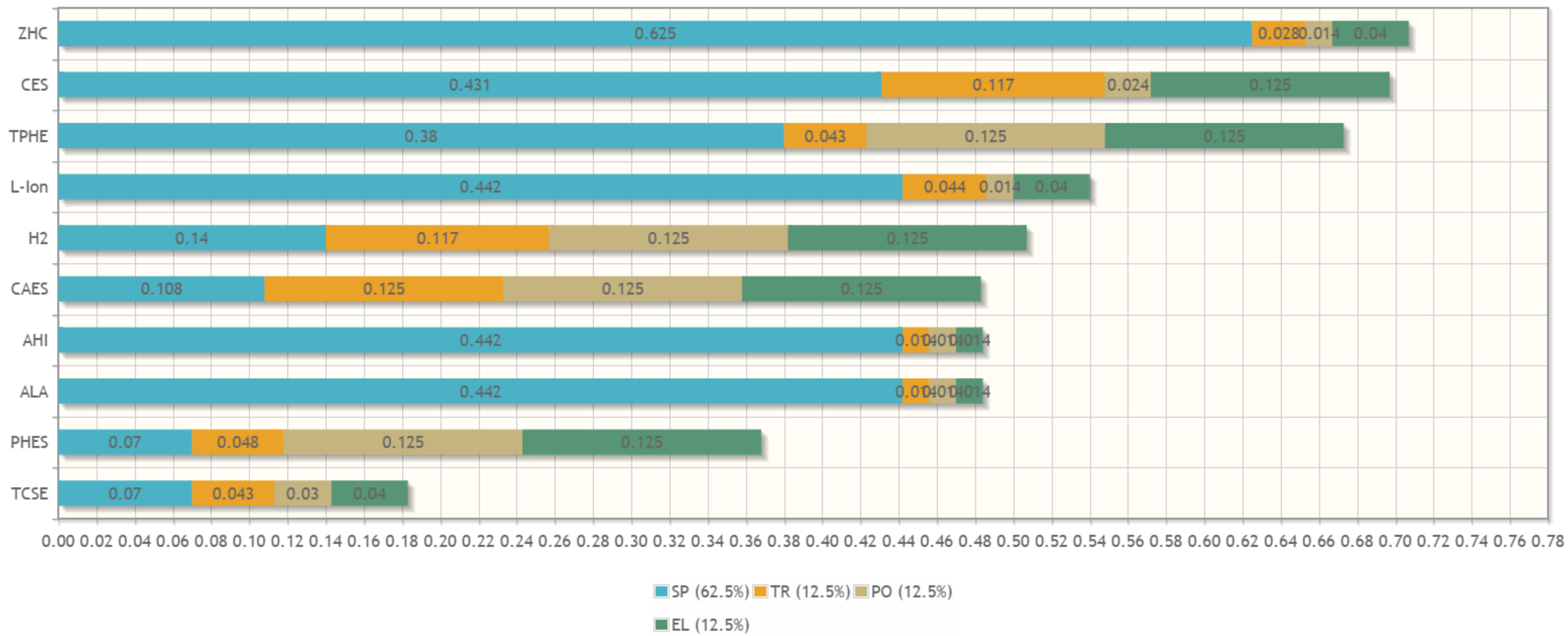

Figure 8 - AHP Final Real Weighting, Space Requirement Priority

(SP – Space Requirements, TR – Operational Temperature Range, PO – Power Output Characteristics, EL – Expected Lifetime of Operation)

8.1.3 Appendix 1-3: AHP Final Real Weighting, Operational Temperature Priority

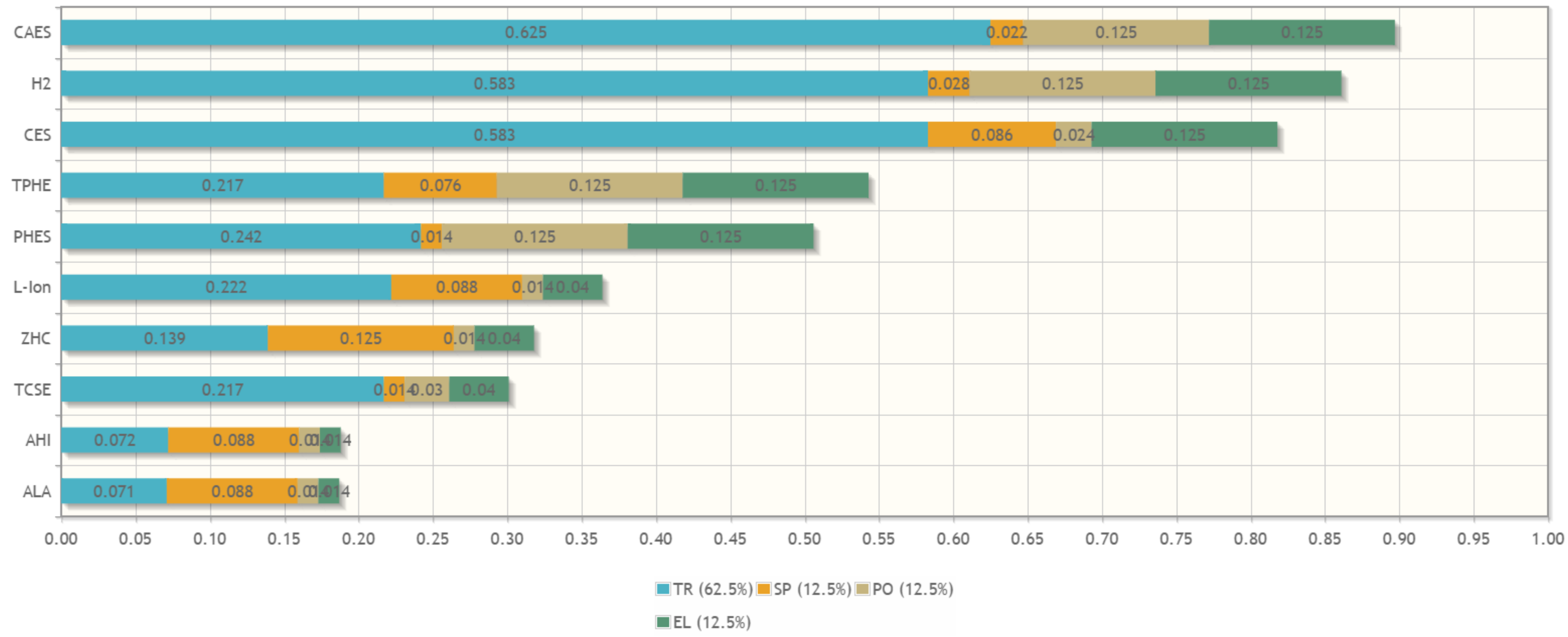

Figure 9 - AHP Final Real Weighting, Operational Temperature Priority

(TR – Operational Temperature Range, SP – Space Requirements, PO – Power Output Characteristics, EL – Expected Lifetime of Operation)

8.1.4 Appendix 1-4: AHP Final Real Weighting, Lifetime of Storage Priority

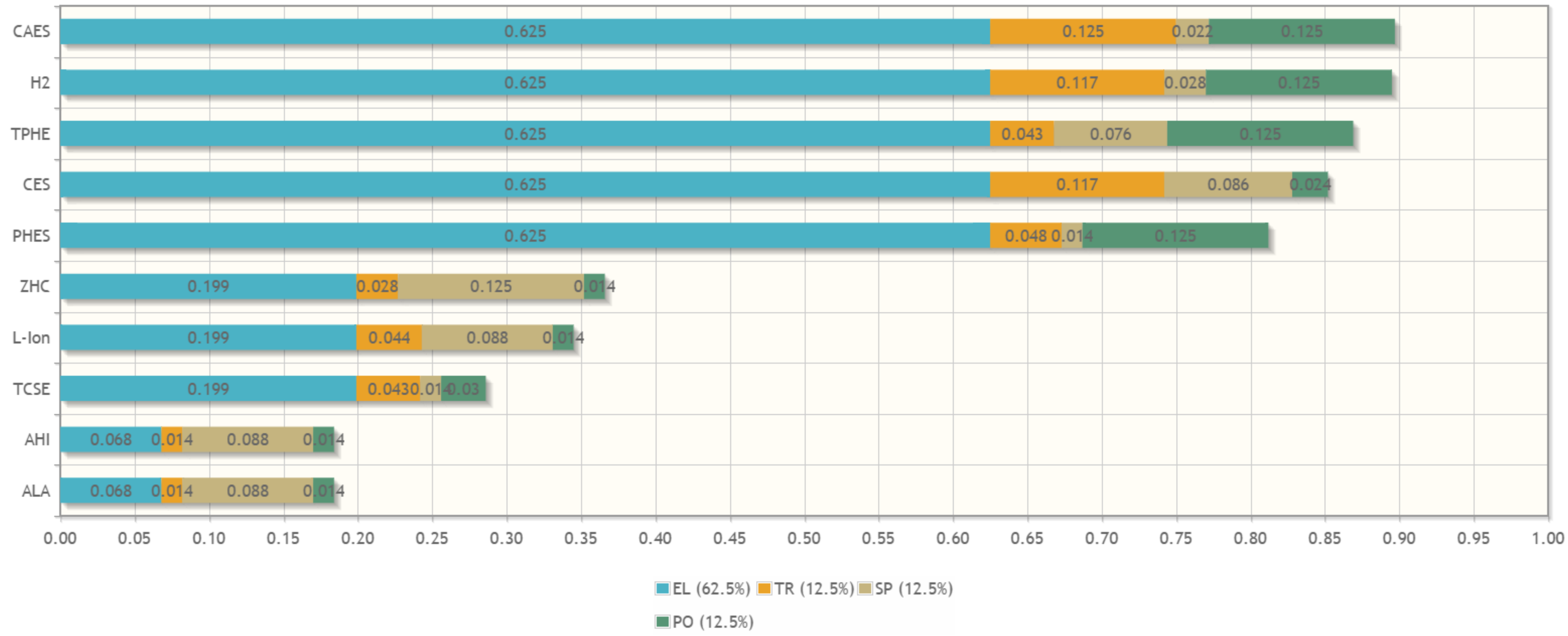

Figure 10 - AHP Final Real Weighting, Lifetime of Storage Priority

(EL – Expected Lifetime of Operation, TR – Operational Temperature Range, SP – Space Requirements, PO – Power Output Characteristics)

8.2 APPENDIX 2: CURRENT STORAGE ENVIRONMENT

Though there is an abundance of technologies that provide the capability to store energy, many of these are not applicable for providing base load power to a mine site. The following section provides an overview of those technologies that are not suited to the task, and a more in depth look at the state of the technologies that have met certain criteria (displayed in section 4.1.2 - Criteria Classification on page 16) and can therefore be looked at as possible solutions for mine site energy storage.

8.2.1 Superconducting Magnetic Energy Storage

The SMES system consists of a superconductive magnet and power conversion module that are stored within a thermally insulating body. The setup allows the storage of electromagnetic energy without the need to change it to a different form (such as chemical or mechanical). This is achieved by creating very intense magnetic fields within the superconductive coil by running a DC current through it. The major losses during storage are due to the present necessity for refrigeration, which maintains the superconductive properties of the coil. Though the output of a SMES system is large enough and its response time is within tens of milliseconds, the duration for which the output can be maintained is in the area of 10 seconds; this is not sufficient for mine site applications unless it is to be solely used as a voltage stability and power quality solution (Seong et al., 2002, Hassenzahl, 1989, Chen et al., 2009).

8.2.2 Flywheel Technology

This technology exploits the mechanical inertia contained within a rotating mass (the flywheel) in order to store energy, converting generated electrical energy into stored mechanical energy. By employing a reversible motor/generator mechanism, the process can be reversed so that the motor that accelerated the mass can act as a generator and extract the mechanical energy out as electrical energy. The physical setup ordinarily makes use of magnetic levitation to support the flywheel within a vacuum so as to minimise losses due to friction. Again the issue arises of output duration, where a flywheel can discharge a large amount of power but for only up to 15-20seconds or so. This groups it with the SMES system as being more useful for ride-through of interruptions or bridging the shift between two base-load sources (Chen et al., 2009).

8.2.3 Super Capacitors

Capacitors store electric charge between two plates with-in a housing, separated by a non-conducting layer (called a dielectric). When a DC-source is applied to one plate and generates a charge on it, an opposing charge will be established on the second plate. Super capacitors differ by storing energy via two solid electrodes separated by an electrolyte solution. The electrodes are commonly made from high surface area materials (such as porous activated carbon). These changes allow for vastly superior surface area and decreased distance between the plates, resulting in storage capacities greater than ordinary capacitors by two orders of magnitude. A primary drawback is again the lack of extended discharge duration (less than one hour) and high energy dissipation due to self-discharge loss (Chen et al., 2008, Chen et al., 2009).

8.2.4 Cryogenic Energy Storage (CES)/ Liquid Air Energy Storage (LAES)

It uses a cryogen (such as liquid air or liquid nitrogen), that is either externally purchased or created at a liquefaction plant by utilising off-peak or excess power, as the medium for storing energy. The cryogen is stored in low pressure, insulated tanks at cryogenic temperatures. To generate power the cryogen is pumped from the tank, via heat exchangers that allow it to contact heat from the surrounding environment, to expand and drive a generating turbine. At this point waste heat can be applied to dramatically increase efficiency. It is also possible to recycle cold air, if that is the cryogen used, that is recovered from the conversion process, to use in air-conditioning. Though it has the ability to generate power for extended periods of time, the efficiency (at only approximately 40-50%) and the total power output (only at the hundreds of kW) are both unacceptable when looking at provision of power to a mine site.

8.2.5 Hydrogen

The 2 most common and applicable methods for generating hydrogen (H_2) are;

Electrolysis - Electrical energy is stored by electrolysing water to produce hydrogen and oxygen. The hydrogen is stored to be utilised in a fuel cell that recombines it with oxygen to generate electricity. The oxygen can be captured and stored to be used in other processes. Heat and water are also released as part of the fuel cell process (Lipman, 2011).

Steam Methane Reforming – utilises a natural gas (or other methane stream – biogas of landfill gas) in an endothermic reaction with water vapour, in the presence of a catalysing agent, to produce hydrogen and carbon dioxide. This CO_2 should be captured to ensure a zero-emissions operation (Riis et al., 2006, Lipman, 2011).

The hydrogen that is produced from either process can be stored as a compressed gas in a pressurised vessel or as a liquid at cryogenic temperatures below -253°C.

In a completely stand-alone application electrolysis is a more appealing alternative as it simply utilises the power produced from a renewable source to generate hydrogen.

A factor that lends itself to the adoption of hydrogen energy storage is that hydrogen is already a very mature market within the chemical industry. All transport and containment infrastructure for hydrogen, in both compressed and liquid states, is founded on tried-and-tested technologies within a supply chain with vast experience.

8.2.6 Pumped Hydro

Pumped Hydro-electrical Storage (PHES) can be divided in to 2 separate methods of implementation, typical above ground storage which utilises damming techniques to create upper and lower reservoirs, and Underground PHES (UPHES) which employs excavation to create underground lower reservoirs and has the upper reservoir situated at ground level.

The standard PHES system requires 2 reservoirs, an upper and a lower, which are connected by a tunnel (the headrace, penstock and tailrace) that houses the pump-turbine and motor-generator. When acting in generator mode, water descends down the penstock and through the turbine, spinning it forward and generating electricity. When needed to store energy, the turbine is supplied with power (i.e. excess generation capacity from a renewable source) which operates in reverse and pumps water from the lower to the upper reservoir via the penstock (Pickard, 2012). The primary problem in application to remote sites is the surface area required for 2 reservoirs, which is expansive, and the specific topographical layout required (elevated catchment zone with lower catchment and runoff area for lower reservoir).

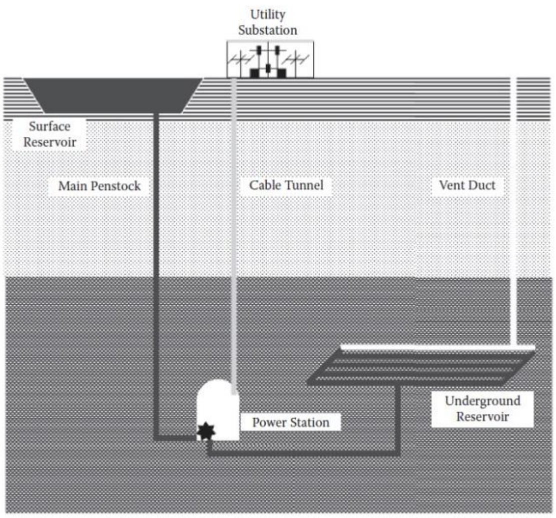

Figure 11- Typical UPHES System

(Barnes and Levine, 2011)

As such, excavating a lower reservoir that is directly beneath the upper reservoir is beneficial, this installation type is Underground PHES (a typical configuration is shown in Figure 11). This essentially halves the ground level surface area required which makes locating an appropriate site relatively easier. The trade-off for less ground level surface area is the prerequisite of good quality, competent rock at depth, beneath the upper reservoir, in which the lower reservoir can be excavated. By creating the reservoirs so, it also reduces the length of headrace and tailrace required and makes them of secondary importance (Pickard, 2012). This is a more suitable installation choice when considering a modular solution as it is applicable for a wider range of geographical locations and has more relaxed requirements.

The economical sizing of a smaller UPHES is a complicated matter; cost of electricity, geological formations, water table characteristics, existing infrastructure, user load profiles, and renewable energy source availability all contribute to optimal sizing of the system (Barnes and Levine, 2011). The obvious major barrier to deployment of UPHES is the difficulty of generating a large, stable water reservoir at a significant depth. For subterranean excavation it is apparent that producing caverns in excess of 10,000m^3 are becoming common operations and thus easier to incorporate into solutions and carry out, so long as the surrounding rock is competent (Tezuka and Seoka, 2003, Glamheden and Curtis, 2006). With some remote mine sites this barrier is eased, as deep excavations are already a part of the mining operation allowing the utilisation of UPHES without further extensive work.

Pending Research and Developments

Over the past four decades many technologies necessary to make UPHES a viable energy storage option have matured, become more prominent and increased in efficiency. Extending the height of the head that hydro-turbines can manage, excavation methods and technologies and geographical analysis techniques have all come further in their fields making the establishment of UPHES systems a more achievable endeavour (Barnes and Levine, 2011). Further research into the much utilised motor-generator turbines is an ongoing investment, as this is an area where improvements can continually be made. Advances in techniques of reducing turbulence in water flow by altering shape and surface finish of the penstock, headrace and tailrace is another area where research is being carried out which may result in small efficiency improvements.

8.2.7 Compressed Air Energy Storage

CAES systems work in essentially the same fashion as conventional gas turbine power plants, though with a few differences that result approximately 3 fold increase in power output. Consider a simplified gas turbine plant that is made up of 4 components; a compressor, a combustion chamber, a turbine and a generator. The compressor injects high pressure air into the combustion chamber at the same time as fuel is injected, this mixture is burnt and heats the air so as to greatly increase its pressure. The high speed vaporous exhaust of this combustion drives the turbine and is then vented. Two thirds of the resultant mechanical energy is reinvested into running the compressor and only one third is actually converted to electrical energy (Crotogino, 2001). The primary difference between this and a CAES system is the separation of the compressing action and the combustion, this is achieved by introducing clutches (allowing the compressor and the turbine to be individually connected to the motor-generator, so they can interact independently with it) and pressure chambers to store the compressed air. During off-peak intervals the compressor fills the pressure chamber so that during peak-demand periods it can be expanded to produce power. This results in 100% of the mechanical energy being converted into electrical, hence the 3 fold increase in output. This has the result of making CAES lower cost on a capital-dollar-input-to-power-output basis than gas turbine plants, as essentially the same setup costs are incorporated but 3 times the output is acquired. A major downside for the system is its need for a combustion agent (such as natural gas), meaning CAES systems cannot be included as part of a fully sustainable, 'clean' energy storage solution. The system on average consumes approximately 33% the amount of premium fuel that conventional combustion turbines do and consequently emits 33% of the pollution that is output from them; though greatly reduced, it hasn't eliminated pollution output or reliance on fuels. To be put to use as a modular energy storage solution, the size, shape and prerequisite characteristics of the compressed air chamber (which for grid storage would need to be an expansive underground cavity) are of utmost importance. Drawing from the Barnes and Levine (2011) theoretically ideal example, the optimal shape is a vertical cylinder with an aspect ratio of 6:1, and the size of the cavity for a 290MW output system, with turbine inlet pressure of 46 bar, is in the area of 130,000 m^3 per hour.

8.2.8 Thermal Energy Storage

TES systems store energy as heat, which can be converted in to electrical energy during peak-demand periods. The principle behind the technology is that of storing energy in materials, and utilising heating and cooling to manage the temperature of said materials. It is preferable for the reservoir materials to be able to handle large changes in internal energy per unit volume so as to minimise the space required for energy storage. There are 3 distinct ways of storing energy;

Sensible heat; based on an actual temperature change in the reservoir material.
Latent heat; works on an isothermal phase change (temperature remains constant throughout) of the material within the reservoir (melting, vaporising, freezing etc.).
Thermochemical heat; the heat of a reversible chemical reaction of the material in the reservoir (Barnes and Levine, 2011).

The ideal storage vessel for the above ground reservoir is of a cylindrical design, as at larger radii the geometry of the cylinder results in greater surface area and also much greater volume. Spherical tanks are much harder to construct, and the storage materials are much harder to tailor for this shape of tank. Underground designs can utilise spherical storage vessels, though the modifying of the storage materials and support structures will inevitably lead to increased costs of setup. These storage tanks make up most of the size of installation, needing a 3,460m^3 tank for 182MWh$_{thermal}$ (which equates to approximately 10MW of electrical power at the Solar One installation in Barstow, CA, USA). For solar thermal installations; the area required for a Parabolic Trough is 5 acres/MW for, 8 acres/MW for a Power Tower installation, and 4 acres/MW for a Stirling Dish (Bhuiyan and Yazdani, 2012). This demonstrates some ability to be modified depending on specific circumstance.

Pumped Heat Electricity Storage

A relatively new application under the sensible heat category. The basis of the most elementary Pumped Heat system, a simplified double thermal energy store apparatus, is that electrical energy is used to drive heat from a 'cold store' to a 'hot store' by means of a heat pump cycle (converting electrical energy to stored thermal energy). Within these 2 thermal stores is a particulate material that allows direct contact between the working fluid (which is pumped from cold store to hot store) and the storage medium. When it is necessary to produce electricity, a power cycle (the reciprocal of the heat pump cycle) converts the thermal energy back to work and electricity (Howes, 2012, Thess, 2013).

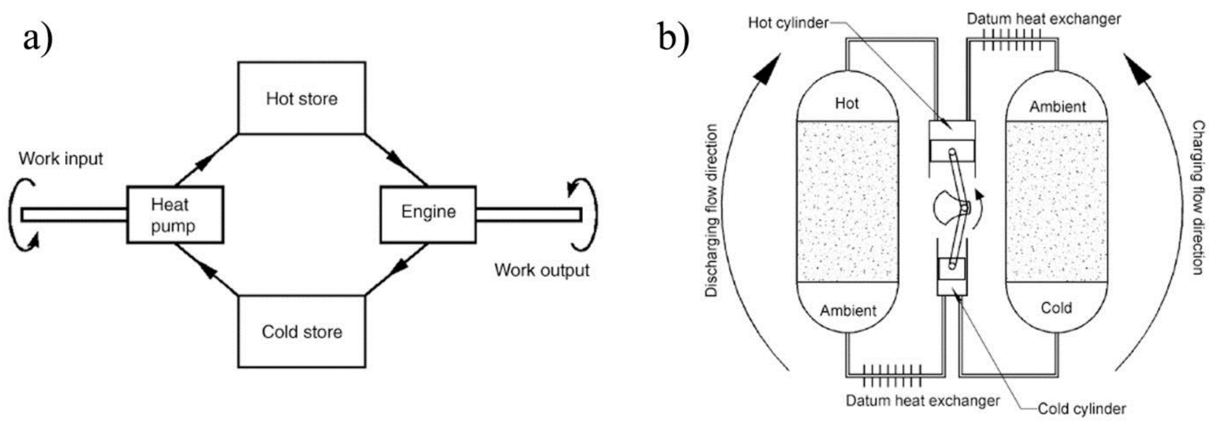

Figure 12 - a) simplified flow diagram of a PHES system, b) simplified schematic of an energy storage system

(Howes, 2012)

Concentrating Solar Power

CSP utilise a combination of lenses and mirrors to concentrate direct beam solar radiation to generate more utilisable forms of energy (such as power or fuels), which is achieved by employing more technologies downstream (Lovegrove, 2012). Unlike flat plate photovoltaics, CSP systems are unable to use solar radiation that has been diffused by dust, clouds or other environmental factors; this means they are primarily suited for locations with a high percentage of clear sky days and low air pollution. The 2 most deployed technologies in this category are the Parabolic Trough and the Central Receiver Tower.

Parabolic Trough – mirrors/ lenses in a parabolic arrangement linearly focus sunlight on to a receiver tube. The entire assembly is mounted on a structure that tracks the motion of the sun along a single axis. Within the receiver tube is a fluid (normally either an oil or molten salt) that transfers the heat to a storage facility. The trough section, along with the receiver tube, can be seen in Figure 13 – a.

Central Receiver Tower – an array of heliostats (two axis tracking mirrors) surround a central tower, focusing solar radiation to a central receiver (like the receiver tube previously) placed atop the tower. This allows more sophisticated, higher efficiency energy conversion at a single point (when compared to the alternative forms of solar focusing). At the receiver is, again, a fluid that transfers the focused heat to a storage facility. An array of heliostats and a central tower is depicted in Figure 13 – b.

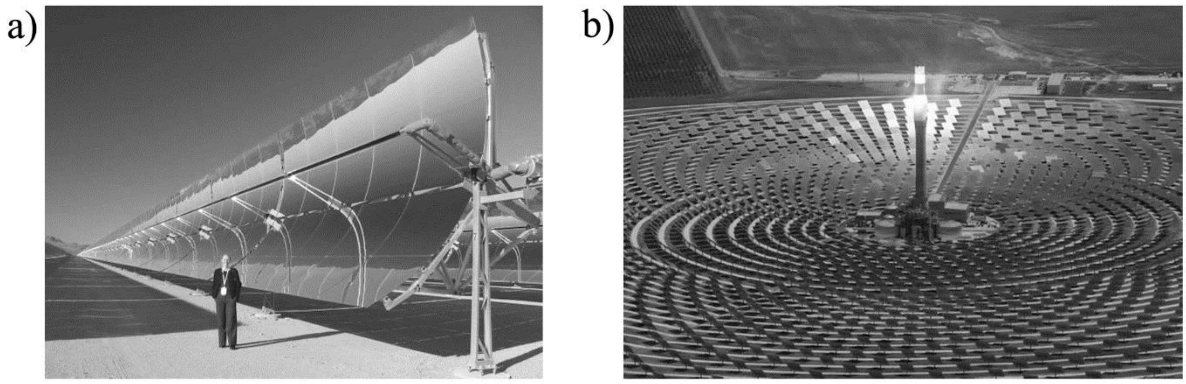

Figure 13 - a) Parabolic Trough Collector, b) Central Receiver System

a) (Nevada Solar 1, picture R Dunn), b) (Gemasolar plant, owned by Torresol Energy) (Lovegrove, 2012, pg. 46)

8.2.9 Electrochemical Energy Storage

There are several electrochemical storage options that have been developed which may be applicable to utility scale energy storage, most of which are under continual development and improvement. The following sections will provide background information into their operation, as well as some strengths and weaknesses and their overall applicability to base-load storage.

Advanced Lead Acid Battery

Over the past 4 decades the lead-acid battery has been the primary heavy duty battery cell utilised by the energy storage market and within the last decade has been the subject of R&D by many companies, resulting in innovations and development of more efficient forms. To begin with, all lead-acid batteries share a common basic chemistry, a positive electrode (lead dioxide) and a negative electrode (metallic lead) where both electrodes are very porous to maximise surface area to increase reaction rate (Barnes and Levine, 2011). From the CSIRO has come the creation of the Ultra Battery, which combines an asymmetric super capacitor electrode with the advanced carbon-lead-acid battery cell into one module. Through use of the capacitor the formulation of lead sulphate deposits inside the negative plate is eliminated, the capacitor achieves this by altering the process of forming and dissolving sulphate crystals on the negative plate upon charge and discharge; overall the roundtrip efficiency is increased (Cooper et al., 2009). Ecoult has used 4 parallel strings of these battery cells, stored in a containerised format for flexibility, to generate 3MW of power for regulation services (Wood, 2013).

Zinc Hybrid Cathode Battery

Another promising developing technology is the Zinc Hybrid Cathode (coined Znyth™) battery being produced by EOS Energy Storage, which boasts a titanium current collector that is permanently conductive, non-corrosive and self-healing, a nearly neutral pH electrolyte with additives and buffering agents that eliminates carbonate clogging issues and improves zinc solubility thus improving energy density and run time. The company also claims that its "hybridisation of cathode chemistries and electro-active catalysts improves power density and roundtrip efficiency" (Amendola, 2014) whilst being produced through a highly standardised manufacturing process that lowers costs. Their current largest modular export is the Eos Aurora which has a capacity of 6 MWh, and is shipped in an ISO 40ft shipping container (standardised for easy integration). This configuration offers a cost of $160/kWh, is projected to last for over 10,000 cycles (38 year calendar life based on 5 cycles per week) and is made from non-toxic materials with no mode of catastrophic failure (Amendola, 2014). Due to its incredibly recent production, the author has not been able to locate any peer-reviewed articles that independently and objectively analyse the Eos Battery solution, but recommends watching this product in the future.

Aqueous Hydrogen Ion Battery

Aqueous Hydrogen Ion (AHI) Technology was developed by Professor Jay Whitacre in response to the growing energy needs he saw globally. He produced a battery using abundant, non-toxic materials and an inexpensive manufacturing technique. The technology comprises saltwater electrolytes, a synthetic cotton separator, carbon composite anode and manganese oxide cathode. This assortment of materials results in a non-combustible and non-toxic product that poses no handling risks and is environmentally friendly. It also uses a non-corrosive reaction at the anode and cathode to prevent deterioration of the inner components. The batteries are shown to have close to 100% columbic efficiency at 1000 cycles, greater than 40wH per kg specific energy capacity and a round trip efficiency of roughly 92%.

The AHI Technology is put to use through the companies S10 battery pack, which consists of 7 B10 batteries. The S10 has a nominal output capability of 48V and capacity of 1.7kWh, and was primarily designed with low cost, moderate to high performance and high levels of modularity in mind. This has resulted in the S10 being able to be deployed in the M100 configuration, or with multiple M100's it can form high voltage output containers or complexes (see figure below).

Figure 14 - variations in deliverable configurations of AHI Technology

(far left - S10, second on left - M100, second from right - sea crate of M100s, far right - high voltage complex of M100s)(Whitacre, 2014)

The M100 weighs 1,285 kilograms and measures 1,063 mm H x 1,321 mm W x 1,016 mm D, which matches the standardised size of industrial pallets, allowing them to utilise mass manufactured storage facilities. The technology has been tested to run at these levels between -5 and 40 Celsius, though is expected to operate according to specifications well above this upper limit (Whitacre, 2013).

Lithium-Ion Battery

The Li-Ion battery houses electrical energy in electrodes of Lithium intercalation compounds, these are lithium compounds into which other specific molecules can be reversibly inserted. Throughout its' operation Li^+ ions translate from anode to cathode via an electrolyte (though it can be solid, liquid or gel, most often a liquid electrolyte with a lithium salt dispersed throughout is used), with reduction and oxidation reactions transpiring at the electrodes (Yang et al., 2011).

There are several primary problems that hinder the use of Li-ion battery packs as utility scale power providers, the first of which is cycle time. AltairNano produced a Li-ion titanate-anode based battery pack that could output at levels of 2MW. The battery pack served well across most rating categories, with a large safe range of temperature operation (-40°C to 260°C), a cycle life of more than ten thousand cycles and decent power density (4kW/ kg), the drawback being that it could only maintain name-tag power for 15 minutes (Yang et al., 2011); this is obviously a critical failure when searching for a utility scale solution. The heat created by Li-ion batteries also provides a barrier to utilisation, as the heat generated at the MW scale must be dissipated very quickly in order to maintain optimal battery operation and safety (the thermal instability of the most common liquid electrolyte described earlier exacerbates this heating problem). If the heat isn't dispersed at a sufficient rate it can cause thermal runaway, with consequences ranging from battery depletion to hazardous explosions; this is especially crucial when batteries are stacked (as in grid storage structures) as the surface-area-to-volume ratio diminishes, resulting in a lesser cooling ability and increased volume which could partake in a thermal runaway chain reaction.

Anode side improvements; Lithium titanate/ graphene spinel is a more recent discovery of a safer assortment of chemicals, it replaces the conventional graphite anode. This configuration sacrifices energy density to a small degree, but undergoes very little structural change (volume expansion throughout chemical reaction) and demonstrates good reversibility; these are characteristics that are sought after for long cycle life applications such as load shifting (Choi et al., 2010).

Pending Research and Developments

Solid state electrolytes are being increasingly employed as they are theoretically safer and longer lasting (Yang et al., 2011), the problem they pose is a costly and impractical assembly process. Due to this unperfected process, solid state electrolytes generally have poor electrochemical activity characteristics (at low temperatures the mobility of the Li^+ ions through the electrolyte is not rapid) which subsequently increases heat production and lowers power output.

On a similar theme, enhancing the rate performance of Li-ion batteries as a whole (including the many electrolyte and electrode combinations) is vital, as it is necessary to achieve increased power and to also reduce the polarization that results from internal resistance; this polarization is a leading cause of heat generation (Choi et al., 2010). Further research into these areas of the technology is required if it is to be adopted as a primary source of renewable energy storage.