INTEGRATION OF RENEWABLES INTO OFF-GRID POWER SYSTEMS.

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1 REPORT

1.1 Introduction

Access to electricity is an essential component of living in the modern world. All countries desire to provide electricity to all their citizens and invest a substantial amount of money in infrastructure. However roughly 2 billion people worldwide, especially those living in rural areas in poorer countries, do not have access to electricity [1]. Most deprived are Southern Asian and Sub-Saharan areas. To for fill their basic energy needs such as lighting these often rural regions depend mainly on expensive fossil fuels such as kerosene for lighting/heating and diesel to produce electricity off-grid. Using these fuels is often inefficient and also comes with high associated CO_2 emissions. The recent sharp rise in fuel prices and the successful development of renewable and sustainable technologies has driven the need for a proper analysis of the suitability of those technologies as a realistic replacement/mitigation of fossil fuel electricity production.

Many systems already integrate renewable energy sources, such as solar and wind power, into off-grid electricity production. As these sources are intermittent in nature these systems are often integrated with diesel generators. To reduce the reliance on fossil fuels by increasing the renewable energy penetration, energy storage technologies can be used to store excess energy produced at times of high renewable energy production to be used at times of low or zero renewable energy production. Energy storage technologies include batteries, pumped hydro; flywheels, super conducting magnetic energy storage; and compressed air energy storage

CAES). Here the suitability of CAES to integrate renewable technologies into off-grid power systems is investigated.

To ensure the successful long term operation of renewable off-grid hybrid systems it is essential that their design ensures that the technology and service providers, consumers, financiers, and government stand to benefit from there installation and operation. In all situations it is necessary to perform the least cost solution to that specific location and set of conditions. The technology used should be chosen on a practical basis and be compared against other system options.

A hybrid system combining the operation of a diesel generator with a renewable energy source, such as solar photovoltaic (PV) or wind power, and an energy storage system should be capable of providing the energy required by the load, obtaining the maximum amount possible from the renewable source whilst also ensuring the quality of the electrical supply.

There are two commercial CAES plants which have been operating over the last few decades, Huntorf (290 MW, 2 hr), Germany and McIntosh (110 MW, 26 hr), Alabama. Apex CAES and Dresser-Rand have partnered on the first new CAES plant project since 1991 and plan to be operating 317 MW CAES by 2017 in Texas [2]. These plants use low cost electricity to run the compressor in an open cycle gas turbine increasing the overall efficiency of the plant. Possibly more relevant to off-grid renewable hybrid systems may be Advanced Adiabatic CAES (AA-CAES) due to the non-reliance on fossil fuels.

The following discussion will cover:

- CAES Operation and Theory
- CAES's Energy/Power storage capabilities.
- CAES's ability to integrate renewable energy systems in to an off-grid power system.
- Review of existing projects using CAES for off-grid systems.
- Conditions required for CAES to be considered.
- Limitations of the storage system.
- Financial analysis of the technology.
- Future developments in the technology.

1.2 CAES Operation and Theory

1.2.1 Theory

The basic theory of storing energy as pressurised air can be described in terms of thermodynamics. Starting with the ideal gas law:

$$PV = nRT$$

Where P is the pressure, V is the volume, n is the amount in moles, R is the ideal gas constant and T the temperature of the gas. If we assume an isothermal process then $T = T_A = T_B$; where T_A and T_B are the temperatures before and after compression respectively.

Then we have the work (energy) needed to compress the air:

$$W_{A\rightarrow B} = \int_{V_A}^{V_B} PdV = \int_{V_A}^{V_B} \frac{nRT}{V} dV = nRT \int_{V_A}^{V_B} \frac{1}{V} dV = nRT \ln(\frac{V_B}{V_A})$$

Considering that $PV = P_A V_A = P_B V_B \therefore \frac{V_A}{V_B} = \frac{P_B}{P_A}$ then we have:

$$W_{A\rightarrow B} = \mathrm{P_A} V_A \ln\left(\frac{P_A}{P_B}\right)$$

Now if we take as an example pressurising air from 1 bar to 70 bar (0.1MPa to 7MPa) in a volume of 1m^3 then we have stored 29.7 MJ or 8.26 kWh of energy. In a more realistic analysis though it is realised that some of the energy is converted, during compression, to heat and is a result of the increased kinetic energies of the molecules within the gas. Additionally the amount of recoverable energy is further reduced by the useful range of pressures required for successful operation of electrical generation machinery. Typically there will be a practical minimum pressure below which the pneumatic motor or turbine will become inefficient [3].

1.2.2 Traditional CAES

CAES is a system in which the compression and then pressurised storage of air is performed. This pressurised air can then, at a later stage when needed, be released and used to generate electricity. Traditionally this storage system is used in conjunction with a gas turbine where the stored compressed air can be released into the combustion chamber of the gas turbines where it is mixed with fuel and ignited. The resulting hot compressed gas is then driven through the turbines rotor blades generating electricity [4]. Figure 1 shows a typical CAES integrated with a gas turbine system.

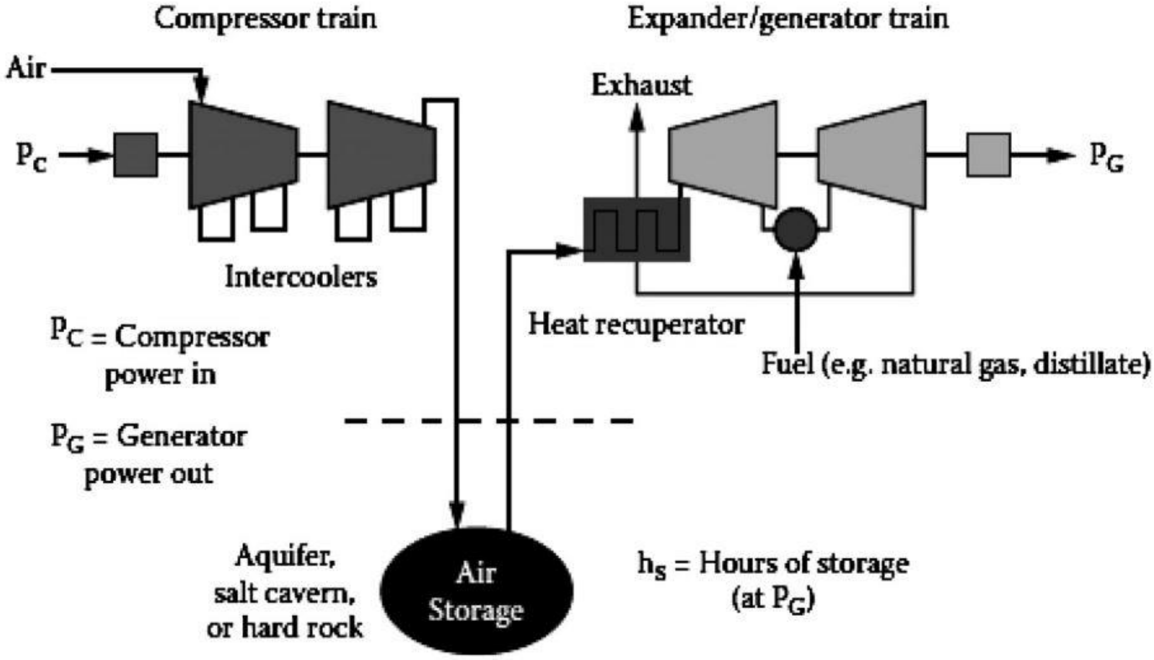

Figure 1 Typical CAES system configuration [5].

1.2.3 Advanced Adiabatic CAES

AA-CAES stores the compression heat in a separate storage unit. The AA-CAES system differs from traditional CAES as it functions without the combustion of natural gas. The first demonstration plant of this kind, ADELE, is in the development stage and is planned to be operating in 2016. ADELE plans to have an electrical output of 90 MW with a storage capacity of 360 MWh and hopes to achieve 70% efficiency [6]. AA-CAES stores surplus energy by the compression of air into a pressurised air store. Thermal Energy Stores (TES) are used to store the heat generated during this compression stage, then later this heat can be recovered and used to reheat the compressed air aiding its expansion through turbines driving generators. ADELE plants compression will be powered by wind turbines and thus emits zero CO_2 during a full cycle. Other CAES Systems

There are a many other CAES systems which have been uncovered in the literature but these have not had the same interest in current research or application as the previously mentioned systems. These include:

- Uncooled Compressed Air Energy Storage which stores the heat in an insulated high pressure chamber with the compressed air. Most suited to short term storage due to the inevitable heat losses.
- Hybrid thermal and CAES is a system in which excess energy is used for the compression of air into high pressure storage cylinders as well as to produce heat which is stored in a thermal storage unit for use in the expansion stage. Such a system can be easily located on an industrial facility.
- Other systems use isothermal processes by exporting the compression heat for use later upon expansion by using various heat exchange processes; such as the use of pneumatic storage systems.

1.2.4 Storage Options

It is possible to store compressed air both above and below ground. The latter of which is more common and for which there are three main types of suitable geological formations: porous media reservoirs (aquifers and depleted gas fields), salt caverns, and rock caverns.

Above ground storage is commonly fabricated from steel and is a much more expensive option due to the material content. However this form of storage provides flexibility of location not reliant on specific natural formations. Beginning January 2013, New York Power Authority (NYPA) in association with EPRI, started constructing a 9 MW CAES demonstration plant to include above ground storage. The plant will store gas at 110 bar and will discharge at 55 bar requiring a storage volume of 1784 m^3. NYPA estimate the project cost (not including the combustion turbine) to be $1,400/kW with operating and maintenance amounting to $3/MWh [7].

A novel approach has been suggested by Pimm et al in which air bags are anchored in deep water potentially offering cost effective high pressure air storage [8, 9]. These underwater pressure bags are under constant pressure and so have isobaric characteristics which are particularly advantageous for the efficient selection of turbine machinery. However losses will be incurred during transportation of the high pressure air due to pressure drops within the pipes and can be approximated as follows:

$$\Delta P = \frac{1}{2}\rho v^2 f \frac{L}{D}$$

Where L is the length of the pipe, D its diameter, f is the friction factor, v is the mean velocity of the air and ρ is the density of the fluid. Hence any such plant would need to be as close as possible to the compression bags to reduce losses due to the pressure drop caused by friction within the pipe.

1.2.5 Suitable Geologies

Table 1 shows a inflation adjusted version of the estimated capital cost of the energy storage component of a CAES system suggested by Eckroad et al [10]

Geology	Capital Cost of Energy Storage
Salt Cavern / Solution Mined	\$1.25/kWh
Salt Cavern / Dry Mined	\$12.5/kWh
Hard Rock / Excavated & Existing Mines	\$37.5/kWh
Porous Rock / Aquifer	\$0.125/kWh
Abandoned Limestone or Coalmines	\$12.5/kWh

1.2.5.1 Salt caverns

The aforementioned traditional CAES plants both use salt cavern air storage. Salt caverns are relatively simple to develop using solution mining techniques and can be a cost effective way of meeting storage needs. It is essential though, if costs are to be kept to a minimum, that there be easy access to an adequate supply of fresh water and also means to dispose of the resulting brine [11]. Salt formations can be bedded or domal both of which can be used for CAES. Salt beds can be more difficult to mine, especially if large volumes of storage are needed, due to the thinner deposits and comparatively high impurities leading to structural instabilities. Whereas caverns mined from domal formations can be deep and narrow as is the case with Huntorf and McIntosh CAES salt caverns.

1.2.5.2 Hard Rock

The cost of mining hard rock is relatively high (see Table 1); although it is possible to use existing mines in which case the cost is reduced by approximately two thirds. Given the high cost of hard rock mining it would not be a first choice to meet storage requirements. Although existing mines are less expensive the relative abundance of such sites is low.

1.2.5.3 Porous Rock

CAES can benefit from what could be the least expensive storage option, aquifers (an underground layer of water-bearing permeable rock), although locating a potential site requires extensive geological characterisation to determine its suitability [11].

1.2.6 CAES Operation

There are a number of different ways in which a CAES system can operate and this depends on the type of geology being used for the storage reservoir. The two families of configurations are those of constant volume and constant pressure. The most prevalent form is CAES operating under constant volume. This means that the storage volume is run over an appropriate pressure range within a fixed volume and can be categorised into two design options: (1) a system in which the inlet pressure to the high pressure turbine is allowed to vary with the cabin pressure (which results in a lower output) or (2) by throttling the inlet pressure so that it remains at a fixed pressure resulting in a constant output allowing for greater turbine efficiencies. However due to throttling losses an increase in the storage volume is required. A CAES system running under constant pressure can also be achieved with the use of a head of water applied by a reservoir at the surface (see Figure 2). In this type of system the losses are minimised and overall system efficiency is increased by the use of the compensated volume. This system would be unadvisable in salt-based caverns and aquifers. The water flow would dissolve the walls of a salt-based cavern and with aquifers flow problems are caused [5]. Hence the CAES under constant pressure system is only advisable for use with reservoirs mined from hard rock.

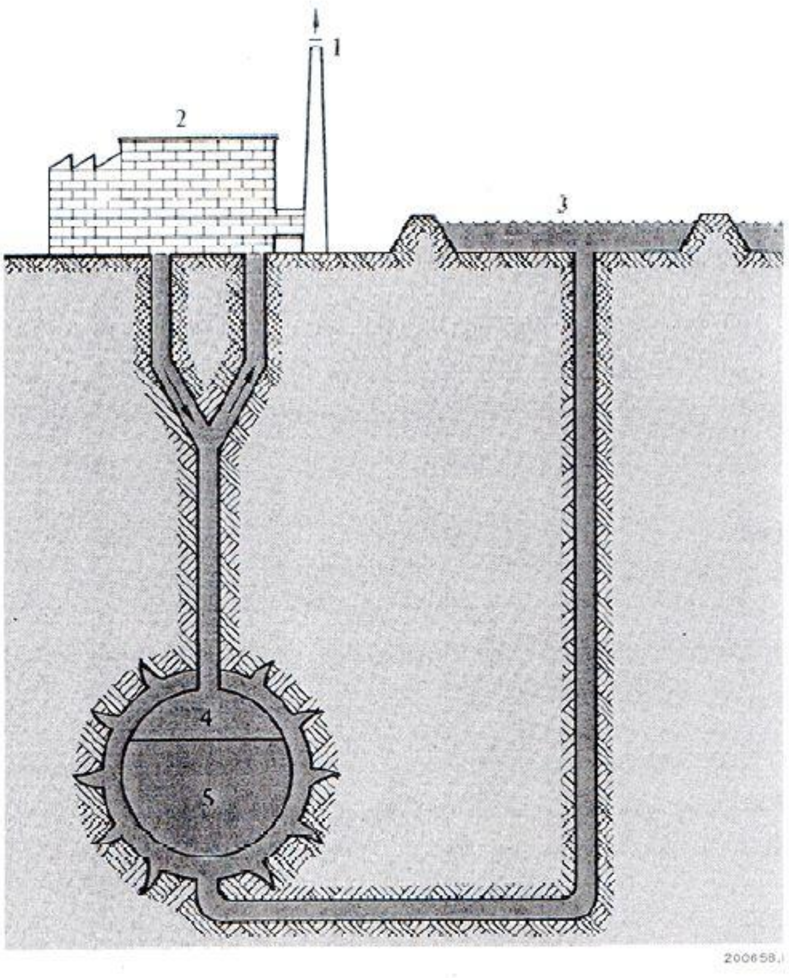

Figure 2 A constant pressure CAES reservoir with compensating water column. (1) Exhaust (2) CAES Plant (3) Surface Reservoir (4) Stored Air (5) Water Column (source [5]).

1.3 CAES’s Energy/Power storage capabilities.

Luo and Wang [6] carried out a comprehensive review of literature within both academic research and industrial application areas and Table 2 shows the main characteristics of CAES found therein.

1.3.1 Rated Power

As indicated in Table 2, conventional in ground CAES have rated power capacities of between 110-300MW [12] with some estimates of capabilities reaching up to 1000 MW [13]. Whereas over ground small scale CAES are rated between 0.003-3MW and potentially reaching 10MW.

Table 2 shows the technical characteristics of large and small CAES systems. Adapted from Luo and Wang[6].

Characteristic	**Units**	**In ground Large Scale CAES**	**Above ground Small Scale CAES**
Energy density	Wh/L	3-6, 2-6	Higher than large-scale CAES
Power density	W/L	0.5–2 , ~ 1	Higher than large-scale CAES
Specific energy	Wh/kg	30–60	140 at 300 bar
Power rating	MW	Up to 300 , 110 & 290, 1000	0.003–3, Potential ~ 10
Rated energy capacity	MWh	~ < 1000, 580 & 2860	~ 0.01, ~ 0.002–0.0083
Daily self-discharge	%	small, almost zero	very small
Lifetime	years	20-40, 30, 20+	23+
Cycling times	Cycles	800-1000	Test 30,000 stop/starts
Discharge efficiencies	%	~70-79	~75-90
Cycle Efficiency	%	42,54 AA-CAES 70	-
Response time		Minutes	Seconds-minutes
Suitable storage duration		Hours-Months, Long term	Hours-Months, Long term
Discharge time at power rating		1-24 h+, 8-20h	30s-40mn, 3h
Power capital cost	$/kW	400-800, 800-1000	517, 1300-1550
Energy capital cost	$/kWh	2-50, 2-120, 2	1MVA from £296k, 200-250
Operating and maintenance cost		0.003 $/kW h, 19-25 $/kW/year	very low
Maturity		CAES commercialized, AA-CAES developing	Early commercialized

Off-grid systems, most commonly, have peak demand in the range (0.5-3.5) MW and not usually exceeding 20MW. The proportion of this to be supplied by CAES in a hybrid system would be dependent on the differences between the demand and renewable generation profiles at any one instance. It could be beneficial to have a CAES rated capacity which could supply the maximum deficit found between renewable generation and the load, especially whilst PV generation is active, to allow the diesel generator to remain switched off. This would allow the diesel generator(s) to be used in the most efficient way. Assuming that this could amount to the majority of the peak load then as can be seen in Table 2 the rated capacity needed falls into the small scale CAES category. This category also gives the added benefit of flexibility of location; not being restricted to geological formations.

However the apparent failure of two recent start-up businesses in this category may be an indication that at present the technology cannot compete with other storage methods and that CAES is more suited to large scale in ground caverns [14]. Due to concerns over the cost effectiveness of small scale CAES it might be more appropriate to consider large scale CAES until there has been successful demonstration of small scale CAES. It can be seen in Table 4 (on page 17) that the rated power of known in ground CAES projects are in the range 0.5-321 MW.

1.3.2 Energy Capacity

To meet the need of a typical off grid rural village, as outlined by Shaahid et al, with an annual energy demand of approximately 16 GWh we could estimate the storage capability needed to be around 30% of the daily demand which equates to 13 MWh. Taking into consideration the minimum and maximum loads of 0.5 and 4.2 MW we can see in Table 4 (on page 17) that many of the existing/planned projects could meet those demands. In suitable locations, with the needed geological formations, it would be possible to mine the storage cavern to the specifications needed according to the site specific optimization results (see section 1.4.1). The energy densities of such site are reported to be in the range 2-6 Wh/l [6], hence to satisfy the above assumptions 2166-6500 m^3 of storage would be required.

1.4 CAES's Ability to Integrate Renewable Energy Systems in to an Off-Grid Power System

There has been, within academia and industrial areas, recent interest in the use of CAES with intermittent renewable energy sources, although predominantly with the smoothing of wind power output [15-22]. One such study investigates the design and operation of wind-diesel-CAES (WDCAS) systems in remote areas of Canada in the hope of reducing both cost and CO_2 emissions of traditional fossil fuel electricity generation [17]. CAES is seen as a storage system which can easily be adapted to the hybrid system, capable of supplying energy in real time and smoothing power fluctuations. This mitigates the need for diesel generators to remain on standby (a waste of fuel), during periods of high wind penetration, in the case of wind speeds suddenly dropping. The authors suggested and analysed several simulated systems with the best achieving cost savings of up to 50%.

A similar system could be envisaged for solar-diesel-CAES (SDCAS). Although there are differences between wind and solar energy capture profiles. Wind speeds can be erratic and the energy is only extractable when its speed is within a certain minimum and maximum thresholds and is dependent on the size of the turbine. At low wind speeds the rotary blades will not turn and at high speeds the machinery needs to be switched off to avoid damage. Wind speeds have a seasonal variability too and are dependent on geo-location.

Solar generation is continuous during daylight hours, although reduced during certain weather conditions, evidently generation is zero otherwise. Solar irradiation levels have a more pronounced seasonal variability than wind speeds and are also dependent on geo-location.

Figure 3 andFigure 4 show typical hourly wind and solar generation averages for different months of the year. It can be seen that solar generation is more predictable and has a steady rise and fall, representing a bell curve, throughout the day. Matching the demand profile, dependent on the particular application of the SDCAS system, will require capturing excess energy at times of high renewable generation and releasing that energy at times of low renewable generation. It might also be beneficial, depending on the results of system optimization (see section 1.4.1), to support the diesel generator during peaks in demand alleviating the need for a backup generator. This could allow for a greater renewable penetration but would be dependent on the site specific characteristics.

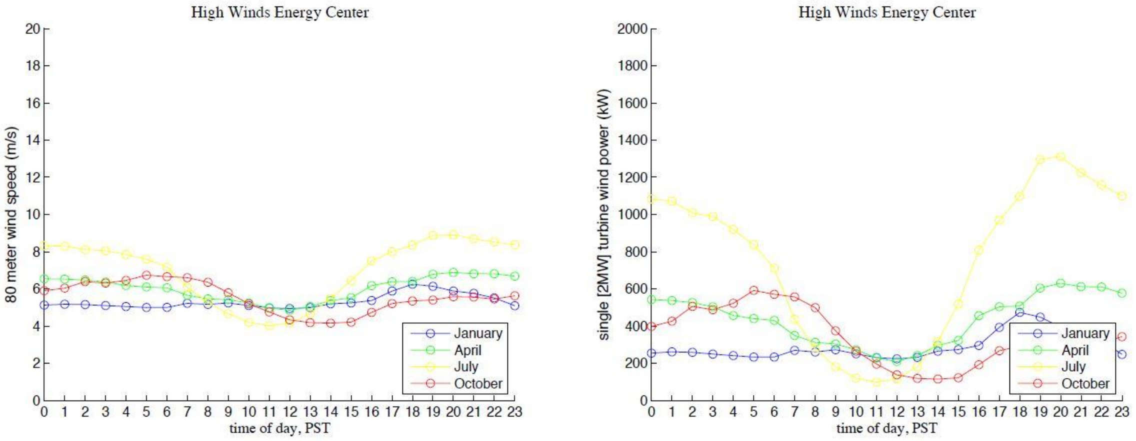

Figure 3 on the left shows a typical average hourly wind speed profile for different months of the year and on the right the corresponding average hourly power output of a 2MW turbine (source [23]).

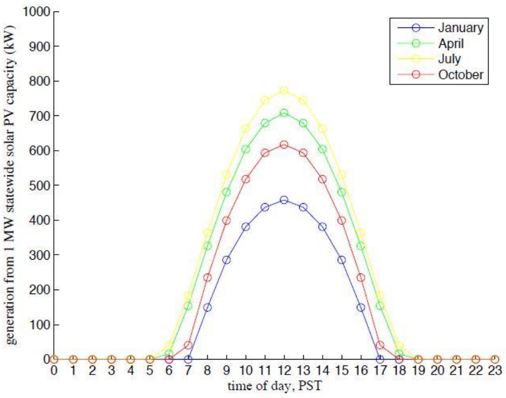

Figure 4 shows a typical average hourly solar generation profile for different months of the year (source [23]).

1.4.1 Optimization and Modelling Software

Due to the complexities caused by the differences in loads and renewable energy source availability in different geolocations it is difficult give a definitive answer as to which configuration of a system supported by CAES would be most profitable, both financially and environmentally, without using site specific optimization. There are a number of microgrid optimization and modelling software available such as HOMER[24], Hybrid2 [25], and RETScreen [26]. Unfortunately none of which have CAES as a storage option within the system design frame work of the software. However optimization could be achieved by building a custom algorithm similar to that proposed by Hussein et al [27].

1.5 Review of Existing Projects Using CAES

Research has been carried out in the area of off-grid and island CAES within academia [17, 18, 28-31] but up to present has not yet been demonstrated. There are however many grid connected CAES projects found globally which can be found listed in Table 3-Table 6 (pages 16-19).

Table 3 shows the known in-ground CAES projects and their expected benefits (source [33]).

Service/Use **Project Name**	Electric Supply Reserve Capacity - Spinning	Frequency Regulation	Electric Energy Time Shift	Renewables Capacity Firming	Black Start	Transmission Congestion Relief	Renewables Energy Time Shift	Electric Supply Capacity	Load Following (Tertiary Balancing)	Onsite Renewable Generation Shifting	Ramping	Electric Supply Reserve Capacity - Non-Spinning	Electric Bill Management
McIntosh CAES Plant	x	x	x										
Pacific Gas and Electric Company Advanced Underground CAES	x	x	x	x									
NYSEG Seneca/Watkins Glen CAES Project	x	x	x		x	x							
Texas Dispatchable Wind	x						x	x	x	x			
Apex Bethel Energy Center		x			x		x				x		
Adele CAES Project			x					x					
Kraftwerk Huntorf	x	x	x		x								
Pollegio-Loderio Tunnel ALACAES Demonstration Plant							x					x	x

Table 4 shows information pertaining to the status and characteristics of all known in-ground CAES projects globally (source [33]).

Project Name	McIntosh CAES Plant	Pacific Gas and Electric Company Advanced Underground CAES	NYSEG Seneca/Watkins Glen CAES Project	Texas Dispatchable Wind	Apex Bethel Energy Center	Adele CAES Project	Kraftwerk Huntorf	Pollegio-Loderio Tunnel ALACAES Demonstration Plant
Technology Type	Natural Gas Combustion Compressed Air	Compressed Air Storage	Compressed Air Storage	Iso-thermal Compressed Air	Compressed Air Storage	Iso-thermal Compressed Air	Natural Gas Combustion Compressed Air	Adiabatic Compressed Air Storage
Rated Power (kW)	110,000	300,000		2,000	317,000	200,000	321,000	500
Duration at Rated Power (Hrs)	26	10		250	96	5	2	4
Status	Operational	Announced	Announced	Operational	Announced	Under Construction	Operational	Under Construction
Country	U.S	U.S	U.S	U.S	U.S	Germany	Germany	Switzerland
Commissioning Date	01.01.1991	01.01.2020		19.12.2012			12.01.1978	01.08.2015
Performance	Burns 30-40% less natural gas than conventional power plants.						42% round trip efficiency	
CAPEX ($million)	65	355	125					4

Table 5 shows the known modular CAES projects and their expected benefits (source [33]).

Service/Use **Project Name**	Renewables Capacity Firming	Electric Supply Reserve Capacity - Spinning	Electric Energy Time Shift	Black Start	Frequency Regulation	Renewables Energy Time Shift	Ramping	Transmission Congestion Relief	Electric Bill Management	On-Site Power
Next Gen CAES using Steel Piping	x	x	x	x	x					
SustainX Inc Isothermal Compressed Air Energy Storage	x					x	x	x		
Highview Pilot Plant	x	x	x			x			x	
ATK Launch Systems Microgrid CAES									x	x
Hydrostor UCAES Demonstration Facility	x					x				
Hydrostor UCAES Aruba Project	x					x				

Table 6 shows information pertaining to the status and characteristics of all known modular CAES projects globally (source [33])

Project Name	Next Gen CAES using Steel Piping	SustainX Inc Isothermal Compressed Air Energy Storage	Highview Pilot Plant	ATK Launch Systems Microgrid CAES	Hydrostor UCAES Demonstration Facility	Hydrostor UCAES Aruba Project
Technology Type	Modular Compressed Air Storage	Modular Iso-thermal Compressed Air	Modular Compressed Air Storage	Modular Compressed Air Storage	Modular Compressed Air Storage	Modular Compressed Air Storage
Rated Power (kW)	9000	1500	350	80	1000	1000
Duration at Rated Power (Hrs)	4.5	1	7	0.75	4	8
Status	Announced	Operational (see section 1.3.1)	Operational	Under Construction	Under Construction	Contracted
Country	United States	United States	United Kingdom	United States	Canada	Netherlands
Commissioning Date			31.07.2011		01.09.2014	
CAPEX ($million)				3.6		

1.6 Conditions Required for CAES to be Considered

The main consideration, until above ground CAES becomes a viable option, for the installation of a CAES system is the available geology. The preferred geology, from a financial perspective, would be porous rock/ aquifers followed by domal salt formations with the means to solution mine (see section 1.2.5.18). The location must be coincident with high average solar irradiation for increased PV electrical generation capability. Other considerations are the proximity of the nearest grid connection; the logistics of supplying the location with fuel and availability of fuel storage. All of which can impact the economic decision to support a PV-diesel hybrid system with CAES to allow higher renewable penetration. Once a possible location has been found a thorough geological survey should be performed to ascertain the suitability of the geological formation for CAES. When all the relevant information has been collected, including load requirements and estimates of possible future growth of the network, a full optimization should be carried out so that the best solution can be compared to other available system options.

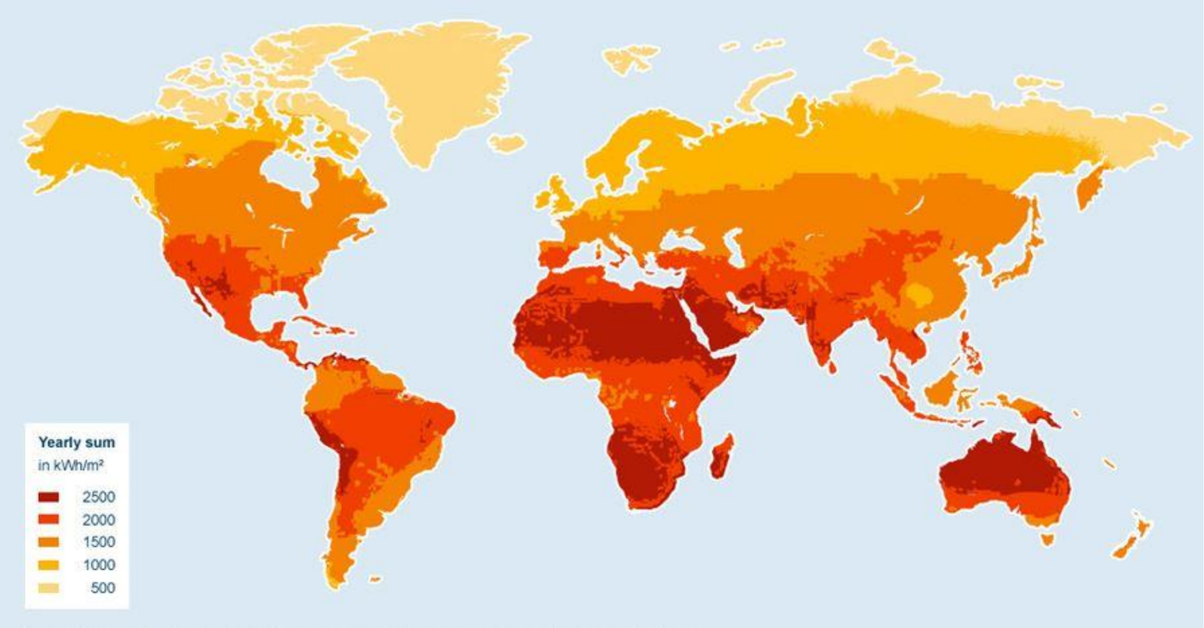

Figure 5 a map showing the variation of solar radiation globally [32].

1.7 Limitations of the Storage System

CAES have relatively low round trip efficiencies when compared to battery technologies, but this could be a reasonable trade off with the added advantage of high life cycle and the low required maintenance. Moreover the CAES is not capable of responding at the fast response times (milliseconds) needed to maintain power quality. However this could be remedied by adding supercapacitors to the system as they are well suited for this service and also possess a high life cycle.

1.8 Financial Analysis of the Technology

Although much research has focused on CAES systems the corresponding detailed techno-economic analysis is not available. Such analysis would give confidence to those seeking to take advantage of this technology and encourage the installation of these systems. However Zakeri et al critically examined the existing literature of life cycle cost of electricity energy storage systems for utility size applications [34]. The difficulty in generalising the cost of CAES systems is attributed to tailoring of technologies to specific locations. It is this lack of information pertaining to the economics of this technology which can deter the deployment of CAES systems. Also a cause for concern is the lack of data available for the costs of the AA-CAES system, which would be most appropriate to remote off-grid locations, since these systems are in the early stages of demonstration.

As was previously indicated salt caverns, porous rock and depleted natural gas fields are the most cost effective storage solutions. In terms of the power train the equipment needed include turbine, compressor (although these can be the same piece of machinery in some systems), and other related equipment. In-ground CAES have a typical construction process lasting three years which should be a determining factor when considering this technology. It is believed that the cost of CAES supporting equipment will not see any significant reduction in the near future due to those technologies relative maturities.

Although AA-CAES technology is estimated to cost 30-40% more than a conventional CAES, plant efficiencies are estimated to rise from 42-54% up to 70% which could offset the additional capital outlay.

Table 7 shows the average cost for various components of a CAES system (source [34]).

Power electronics	914 $/kW (AA-CAES, 1188-1280 $/kW)
Storage	40 $/kWh
Operation and maintenance	3.9 $/kW-yr
Total capital cost	893 $/kW

1.9 Future Developments in the Technology

AA-CAES is a promising technology for off-grid applications as it is capable of operating without the need for fossil fuels. With a demonstration plant soon to be operating (August 2015) in the Pollegio-Loderio Tunnel ALACAES project this technology may prove itself to be a realistic choice for support of future hybrid systems. As can be seen in Table 3Table 6 (on pages 16-19) there are many different CAES technologies being demonstrated and commercialized. It is hoped that information regarding the techno-economic benefits of those systems will be desimnated in a way which will allow more confident decisions to be made about future CAES system installations.

Note: The Electric Power Research Institute EPRI intends to release a CAES guidebook in 2015 which intends to address the CAES system costs and benefits and will help those considering the construction of such a plant [35].

1.10 Conclusions

CAES can help integrate intermittent renewable resources into off-grid networks and is a market ready technology. However if the system is to be cost effective then the CAES system and specific plant parameters will require an effective design and proper analysis of economic-thermodynamic trade-offs. The available geology should be the main consideration, at least until above ground systems become more economically viable, as this will be the most efficient way to reduce the overall cost of the plant.

1.11 Nomenclature

AA-CAES	Advanced Adiabatic CAES
CAES	Compressed Air Energy Storage
EPRI	Electric Power Research Institute
NYPA	New York Power Authority
PV	Photovoltaic
SDCAS	Solar-Diesel-CAES
TES	Thermal Energy Stores
WDCAS	Wind-Diesel-CAES

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