

A Review of Compressed Air Energy Storage Technology for Renewable Energy Storage in the Sudano-Sahelian Zone of Nigeria

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Abstract

Electrical energy storage has been identified as the basic founding technology to meet the challenges in the power network due to the rapidly increasing penetration of renewable energy. Compressed Air Energy Storage (CAES) has gained substantial worldwide attention in recent years due to its low-cost and high-reliability in the large-scale energy storage systems. Reviews of different CAES technologies were discussed; Small-scale CAESs are more suitable for integration with renewable energy for back-up, load following and uninterruptible power supply. Wind and solar energy technologies in Sudano-Sahelian Zone were also presented. The potentials of both wind and solar energy in the study area, is highly sufficient for electrical power generation and storage. The paper provided the essential and critical information for CAES plant planning and building. The re-generation of the stored renewable Energy electrical energy from the compressed air was also presented.

Keywords: Compressed Air, Electrical Energy Storage, Renewable Energy, Wind, Solar, Compressors, Expanders, Reservoirs.

Introduction

The world is faced with the challenges of economic growth and reducing its dependence on fossil fuels in order to protect the environment. Different methods are being used to reduce the consumption of energy from fossil fuel sources by improving energy efficiency and exploring sustainable, clean renewable energy sources (Wang *et al.*, 2013; Li *et al.*, 2015). Currently, there has been rapid development in solar, wind, and other sustainable energy sources. Solar Photovoltaic energy is considered one of the renewable energies with great development potential in the 21st century. However, the high level of penetration of solar power generation globally increased the hope for large-scale power generation for grid-connected utilization, and the intermittent nature of solar energy is a serious concern. Hence, Suitable solutions are urgently required, and energy storage has been identified as one of the most promising technologies for addressing the problems (Xu *et al.*, 2013; Liu *et al.*, 2015).

Energy storage, especially pump hydro-power storage (PHS), was the major energy storage technology used for a long time for the grid during high demand. Coal and gas were historically the major sources of energy. As the technology developed, many energy

storage techniques emerged on the market. At the Energy Storage China, 2016 conference, the Chinese Alliance for Energy Storage revealed that China had in operation 118 energy storage technologies employing lead acid batteries, Li-ion batteries, flow batteries, and excluding PHS, CAES, and thermal energy storage. This represents 105.5 MW of installed energy capacity with a 110% annual growth rate (2010–2015), meaning a predicted installed capacity of up to 24.2 GW and 40 GW (including PHS) by 2020 (China, 2016).

PHS is one of the most widely used energy storage technologies, which has demonstrated its merits in terms of technological maturity, high cycle efficiency, large rated power, long service life, and low operating cost, but the location choices are highly restricted, construction cycles are long, maintenance costs are high, and it impacts the local environment, so the further utilization of PHS is limited (Pickard, 2012; Jan 2015). In addition to PHS, CAES is another feasible way to realize large-scale power storage. Energy storage can be organized into several categories based on the nature of its operation and storage medium used: primary fuels such as coal, oil storage, etc.; intermediate fuels (such as gas, hydrogen, etc.), electrical energy storage, and other forms (Wang et al., 2013). The recent status of electrical energy storage technologies is presented in Table 1 (Luo et al.; Kousksou *et al.*; and Sameer, 2015), along with the cost of different energy storage technologies. is presented in the Table 1 (Luo *et al.*; 2014, Kousksou *et al.*;2014 and Sameer, 2015) and the cost of different energy storage technologies, is shown in Figure 1, including the capital energy cost pitted against capital power cost.

Table 1. Technical Characteristics of Electrical Energy Technologies

Technology	Energy Density (Wh/L)	Power Rating (MW)	Suitable Storage Duration	Lifetime (years)	Discharge Time	Cycling Times (cycles)	Maturity
PHS	0.5–2	30–5000	H-Mon	40–60	1–24 H+	10,000–30,000	Mature
Flywheel	20–80	0.1–20	Sec-Min	15–20	Sec-15 Min	20,000	Early Com
CAES	2–6	≥300	H-Mon	20–40	1–24 H+	8000–12,000	Early Com
Capacitor	2–6	0–0.05	Sec-H	1–10	Millis-1 H	50,000+	Com
SMES	0.2–6	0.1–10	Millis-H	20–30	≥30 Min	10,000+	Demo/Early Com
TES	80–500	0.1–300	Min-Days	5–30	1–24 H+	-	Demo/Early Com
Solar fuel	500–10,000	0–10	H-Mon	-	1–24 H+		Developing
Hydrogen fuel cell	500–3000	0–50	H-mon	5–20	Sec-24 H+	1000+	Developing/Demo
Li-ion	150–500	0–100	Min-Days	5–15	Min-H	1000–10,000	Demo
Lead-acid	50–90	0–40	Min-Days	5–15	Sec-H	500–10,000	Mature

Abbreviations: SMES, Superconducting magnetic energy storage; TES, Thermal energy storage.

(Luo, *et al.*; 2014, Kousksou, *et al.*;2014 and Sameer,2015)

In more detail, a careful comparative life cycle cost (LCC) analysis of electricity storage. Systems were provided by Zakeri and Syri, and the LCC of a CAES plant is highly, dependent on fuel costs, emissions costs, and electricity prices (Zakeri and Syri, 2015). Comparing the investment cost, capacity, lifetime, energy density, and storage duration, PHS and CAES are suitable for use in large-scale commercial applications where they are more economic.

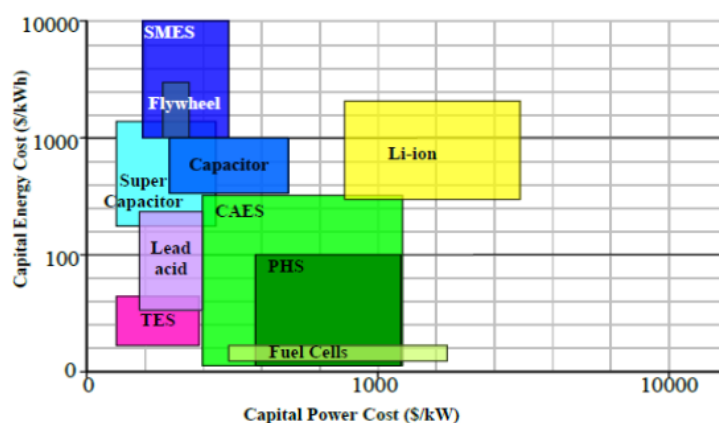


Fig. 1. Capital Energy Cost vs Power Cost ((Luo, *et al*; 2014, and Kousksou *et al*; 2014 and Sameer, 2015).

The Sudano-Sahelian zone of Nigeria is blessed with abundant solar radiation and wind energy potentials. To utilize this renewable energy for the electricity needs of the zone and the country at large, a better energy storage option is required. Hence, this paper presents a review of Compressed Air Energy Storage (CAES) technologies and renewable energy technologies (solar and wind energy technologies). CAES-like Pump Hydro Energy Storage (PHES) will store the energy from the sun (solar) and wind energy in the form of compressed air during peak periods

Statement of Problem

The main problem with Compressed Air Energy Storage (CAES), is its low energy efficiency. During compressing air, some energy is lost due to heat generated during compression, which cannot be fully recovered. However, Compressed Air Energy Storage has gained substantial worldwide attention in recent years due to its low-cost and high-consistency in the large-scale energy storage systems.

Objectives

The objective of this review work is to accomplish a technical valuation of compressed air energy storage technology for renewable energy storage in the sudan-sahelian zone of Nigeria, using Solar Photo-Voltaic, energy design factor.

Methodology

A small-size CAES system is made up of a compression section, a high-pressure vessel, and an air expansion section, according to the performance of the system, which is determined using information from the operation of a tiny prototype and the findings of the thermodynamic model. The air storage section can be constructed with a custom-fitted storage vessel. A solar PV system was used to drive the motor that compresses air into the storage reservoir. In the same way, because of wind energy potentials in the study area, wind energy serves as a prime mover for the electrical motor that will compress air into a

reservoir. Therefore, in this review work, the Sudan-Sahelian zone of Nigeria is presented. Solar energy technologies were presented, as well as wind energy. and the stored energy was used during off-peak periods.

Area of Study

The Sudano-Sahelian Zone in Nigeria is located between longitude 4° and $14^{\circ}E$ and latitude 10° and $14^{\circ}N$ and lies immediately to the south of Sahara Desert. It is located in the northern part of Nigeria and stretches from the Sokoto plains to the Chad basin (Odekunle, *et al*; 2008). The zone span roughly through Sokoto, Zamfara, Katsina, Kano, Jigawa, Yobe, Borno states and some areas in Adamawa state respectively (Jidauna *et al*;, 2011). The area also includes part of Bauchi.

Fig. 2. shows the map of the study area. The Sudano-Sahelian zone of Nigeria occupies almost one-third of the total land area of Nigeria (Odekunle *et al*., 2008). The zone houses over one-quarter of the Nigerian population (FMEN, 2006). According to the 2006 population census, the total population of the zone is 32,954,538. The choice of the study area is based on the vegetation characteristics and climatic conditions of the zone. The zone is predominantly a Savannah area with grasses and short trees, which have little impact or effect on wind speed and direction, and also long hours of solar radiation and sunshine. In terms of climate, wind speed is relatively high in the area because of its The vegetation of the Sudano-Sahelian zone is of the Savanna type, consisting of Sudan and Sahel, with the density of trees and other plants decreasing as one moves northward (Abaje, 2007). It is characterized by abundant short grasses of 1.5–2 m and few stunted trees hardly above 15m (online Nigeria, 2002). The Sahel Savanna, on the other hand, is the last vegetation belt to the north of Nigeria, with proximity to the fringes of the fast-encroaching Sahara Desert. It is characterized by very short grasses of not more than one meter high located in between sand dunes. The area is dominated by several varieties of acacia and date palms. closeness to the Sahara desert

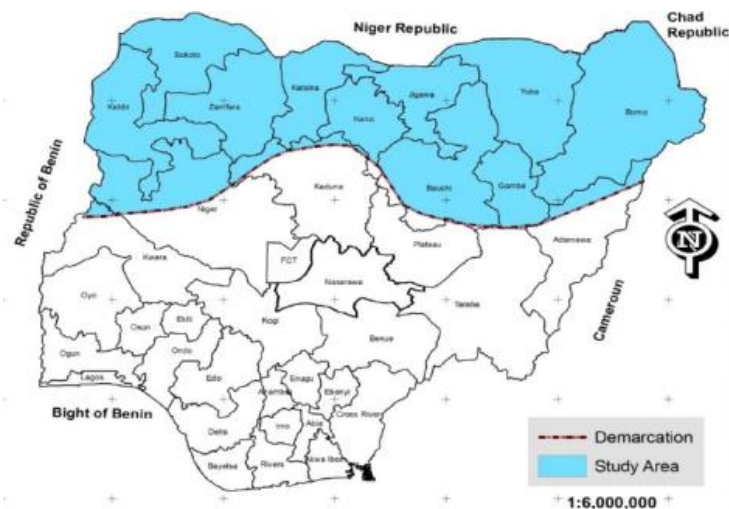


Fig. 2. Map of Nigeria showing the study area, Sudan-Sahelian Zone (Irwana,*et al*; 2013, Ifabiye *et al*; 2017)

Wind Energy Technologies

Wind energy generation is the fastest growing renewable energy market worldwide. The global cumulative installed wind power generation, and has gradually increased from 6100MW in 1996 to 158,505MW in 2009. But, this installed capacity is expected grow up to 238GW and will play a crucial role in mitigating future greenhouse gas (GHG) Emissions (world wind energy report 2008).

Wind speed in Nigeria ranges from 4.0 - 5.12 m/s in the extreme northern part of the country, while 1.4 - 3.0 m/s in the southern Nigeria. Just like South Africa, the Sudano-sahelian region of Nigeria has a wind speed that ranges from 4.0 m/s to 5.0 m/s in this region but increasing approximately to 8.0 m/s in some mountainous areas (Chineke, 2009). A study carried out by the energy commission of Nigeria (ECN) reveals that the exploitable wind energy reserve at 10m height may vary from 8MW/h/yr Yola to 51MW/h/yr in mountainous areas of Jos, and could reach as high as 97MWh/yr in Sokoto (Oloeje, 2004).

The potential of wind energy generation has been examined in sudano Sahelian region of Nigeria. It was revealed that wind energy potential in the area is high if larger rotor diameter and efficient wind turbines were used. Eight-nine percent of annual wind speed was found to be above the threshold unit of 3.0m/s for wind turbine operations. About 512,260 kW of electricity can be generated in the area. Therefore, both the government and the private sector should take the advantage of the abundant wind resource in the area for energy generation (Ifabiyi *et al*; 2017)

A potential estimate of wind speeds for 10 selected sites in Nigeria render the speed between 3.6 m/s to 5.4 m/s. this result was compared with the result obtained from calculated wind speed using climate Model Mainz, gives a discrepancy of -4.3% to 4.1%, which lies within the acceptable limit of error. The results of 10 sites are as presented in table 2.

Table 2. Summary of measured data of annual wind speeds. Source: Wind Energy Resources Mapping as reported by (Ubong *et al*; 2021).

Sites	Land Use Type	Altitude (m)	Height (m)	Windspeed (m/s)		Difference %
				Measured	KLIMM	
Enugu	Complex Landscape	466	30	4.6	4.4	-4.3
Jos	Complex Landscape	1344	30	5.2	5.1	-1.9
Pankshin	Complex Landscape	1355	40	4.9	4.7	-4.1
Sokoto	Plain Surface	352	30	5.4	5.2	-3.7
Kano	Plain Surface	340	30	4.9	5.1	4.1

Gumel	Plain Surface	393	30	4.1	4.2	2.4
Maiduguri	Plain Surface	373	30	4.7	4.6	-3
Ibi	River Valley	300	30	3.6	3.3	-8.3
Gembu	Highly Complex Landscape	1800	40	5	5.2	1
Lagos	Coastal Area	2	30	4.7	4.9	4.3

Solar Energy Technologies

Solar Energy provides cheap and abundant Energy for the communities in the Sudano-Sahelian region of Nigeria owing to the abundant sunlight radiation in the region almost throughout the year. Connection to the national grid may not be economical viable because of its distance from the national grid, this region receives more solar radiation and sunshine than any region in the country (Shaaban and Petinrin, 2014).

Table 3. Maximum, minimum and yearly average global solar radiation (kwh/day), (Albert et al; 2023)

Stations	LLat. N°	LLong. E°	Alt (m)	Max	Min	M Avg
Abeokuta	7.25	3.42	150	4.819	3.474	4.258
Abuja	9.27	7.03	305	5.899	4.359	5.377
Akure	7.25	5.08	295	5.172	3.811	4.485
Azare	11.8	10.3	380	6.028	5.022	5.571
Bauchi	10.37	9.8	666.5	6.134	4.886	5.714
Benin city	6.32	5.6	77.52	4.615	3.616	4.02
Calabar	4.97	8.35	6.314	4.545	3.324	3.925
Enugu	6.47	7.55	141.5	5.085	3.974	4.539
Ibadan	7.43	3.9	227.23	5.185	3.622	4.616
Ilorin	8.48	4.58	307.3	5.544	4.096	4.979
Jos	9.87	4.97	1285.58	6.536	4.539	5.653
Kaduna	10.6	7.45	645.38	6.107	4.446	5.672
Kano	12.05	8.53	472.14	6.391	5.563	6.003
Katsina	13.02	7.68	517.2	5.855	3.656	4.766
Lagos	6.58	3.33	39.35	5.013	3.771	4.256
Lokoja	7.78	6.74	151.4	5.639	4.68	5.035

Maiduguri	11.85	13.08	383.8	6.754	5.426	6.176
Markudi	7.73	8.53	112.85	5.656	4.41	5.077
Minna	9.62	6.53	258.64	5.897	4.41	5.427
N. Bussa	9.7	4.48	152	5.533	4.15	4.952
Nguru	12.9	10.47	342	8.004	6.326	6.966
Obudu	6.63	9.08	305	5.151	3.375	4.224
Oweri	5.48	7.03	120	4.649	3.684	4.146
P/H-court	4.85	7.02	19.55	4.576	3.543	4.023
Serti	7.5	11.3	610	4.727	3.972	4.488
Sokoto	13.02	5.25	350.75	6.29	5.221	5.92
Wari	5.52	5.73	6.1	4.237	3.261	3.748
Yola	9.23	12.47	186.05	6.371	4.974	5.774

Solar energy is the most promising of the renewable energy resources in the region, the energy radiated from the sun is about $3.8 \times 10^{23} kW$, which is about 1.082 million ton of oil equivalent (mote) per day. This is about 4000 times the daily current crude oil production in Nigeria and about 13,000 times the natural gas daily production, based on the standard energy units (Idigbe and Onohaebi, 2009). Nigeria has an average of $1.804 \times 10^{15} kWh$ of solar radiation incidents annually based on Nigerian land area of $924 \times 10^3 km^2$ and an average of $5.535 kWh/m^2/day$. The sun shines on the average for $6.5h/day$. The annual solar energy value is about 27 times the country's total fossil energy resources in energy units and is over 115,000 times the electrical power produced (Augustine and Nnabuchi, 2009). Therefore, only about 3.7% Nigeria's land area is required to collect an amount of solar energy equal to the country's conventional energy reserves. The monthly global solar radiation in Nigeria for a period of 25 years is shown on a table 3 above.

Compressed Air Energy Storage Technologies

In general, a CAES system refers to a process of converting electrical energy to a form of compressed air for energy storage and then it is converted back to electricity when needed. An illustrated conventional CAES system is plotted in Fig. 1. During the charge process, air is pressurized by compressors which are driven by motors using off-peak electricity from the grid or/and renewable energy. Before the storage and the compression, the compressed air flow through interconnected heat ex-changers or other heat sinks to decrease its temperature. During the discharge period, the compressed air is heated first by the heat ex-changers or other heat sources and produce work by ex-panders. The mechanical work is converted to electricity by connecting electric generators to the ex-pander's shaft. Five major sub-processes formulate a complete CAES system: 1) air compression; 2) heat exchanges during both charge and discharge; 3) air expansion; 4) compressed air storage in cavity or pressure container/tank; and 5) mechanical transmission between motor, generator, compressor, and ex-pander. Depending on the scale of a CAES system, it can be

roughly divided into large-scale CAES (> 100MW), micro-scale CAES (tens of kW) and small-scale CAES ranged in between. Large-scale CAES systems are normally built for grid applications in load shifting, peak shaving, and frequency/voltage control (Luo *et al*; 2017). Small-scale CAESs are more suitable for integration with renewable energy for back-up, load following and uninterruptible power supply. An application of small-scale CAES system for load following was presented in (Salvini *et al*; 2017) in which an approach of investigating and controlling was also used to minimise the specific compression work. Micro-scale CAES is capable to be used in a multipurpose system. A good example of a micro-scale CAES combines energy storage, air cycle heating and cooling was analyzed in (Kim Y, and Favrat D., 2010). Proper types of expansion machines suit different CAES system scales and operations. High performance of these systems is only achieved when appropriate compressors and ex-panders are selected. As a matter of fact, overall performance of a CAES system significantly affected by the efficiencies of air compression and expansion processes, because they are the “interfaces” to transfer different energies where significant energy loss normally occurs.

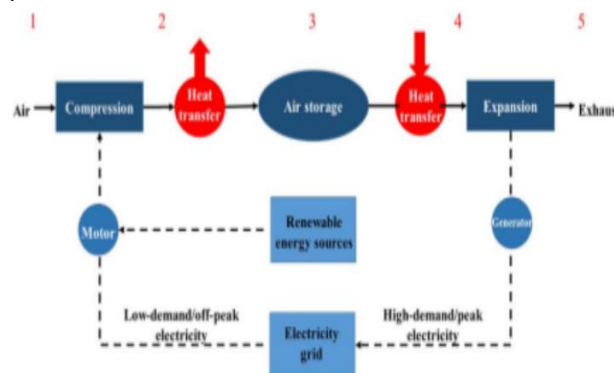


Fig. 3. Schematic diagram of a conventional CAES

The performance of a CAES system coupled to a PV plant is studied as a storage system for building applications by the combination of data from the operation of a small-size prototype and the results of the thermodynamic model. The small-size CAES system is composed by a compression section, a high-pressure vessel, and an air expansion section. The air storage section can be constituted by a custom-fitted storage vessel. The small-size prototype was designed, assembled, and installed in the Laboratory of Applied Physics of the Engineering Department of Terni, University of Perugia. The proposed thermodynamic model was used to investigate and predict the overall electrical efficiency, considering the energy absorbed by the compression section, constituted by the excess power supplied by the PV system, and the energy produced by the expansion section. The compressed air at 30 bars was stored in a vessel with a volume of 1.7 m³. Considering that the minimum pressure inside the vessel is four bars, the quasi-turbine elaborates a flow rate of 0.024 kg s⁻¹ for a maximum period of 38 min. The expansion phase produces 1.008 kWh, which covers 21.9% of the residential energy demand. The electrical efficiency of a daily cycle is equal to 11.6%.

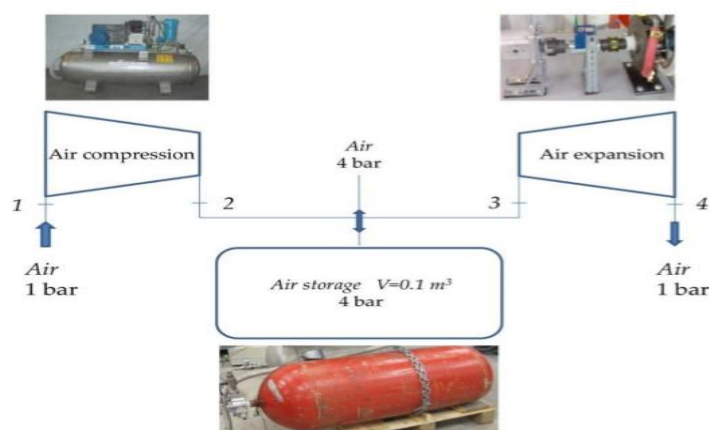


Fig. 4. Experimental apparatus

Description of CAES Technologies

CAES refers to the energy stored in the form of high pressure compressed air and consumed in a different form of energy converted from the compressed air. In supporting power network operation, compressed air energy storage works by compressing air to high pressure using compressors during the periods of low electric energy demand and then the stored compressed air is released to drive an ex-pander for electricity generation to meet high load demand during the peak time periods, as illustrated in Figure 3.

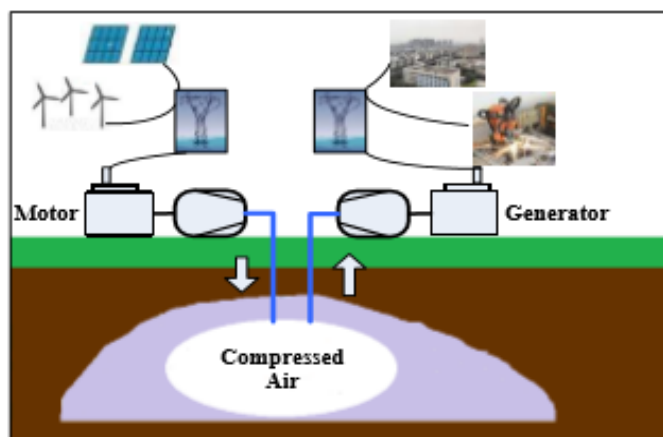


Fig. 5. Illustration of Compressed Air Energy Storage

For a CAES plant, as shown in Figure 5, there are two different stages of operation, namely compression and expansion. Since the two stages do not run simultaneously, there is higher system efficiency (48–54%) than in traditional gas turbine systems. At present, two large scale commercial CAES plants scale commercial CAES plants involving gas fires are in operation. The first CAES plant was installed and commissioned for operation in Huntorf Germany in 1978 (Luo, *et al*; 2015). It has a rated power generation capacity of 290MW for providing load following service and meeting the peak demand while maintaining the

constant capacity factor of a nuclear power plant. In 1991, the second large-scale CAES plant commenced operation in McIntosh United State of America (USA) in 1991 (Luo, *et al*; 2015). This plant has a generation capacity of 110MW, with a storage capacity of 2700 MW/h, and is capable of continuously delivering its full power output for up to 26 hrs. A CAES system has the following primary components: (1) compressors; (2) ex-panders; (3) air reservoirs.

Compressors

Compressors and ex-panders are designed, or selected, according to the applications and the designed storage pressure of the air. The pressure of air in a vehicle cylinder can reach 30 MPa of storage pressure for higher energy storage density in a limited volume, so multi-stage reciprocating compressors are normally adopted. The pressure used for a large scale CAES system is about 8 MPa, for which multi-stage compressors are used, and normally combined axial flow compressors and centrifugal compressors are selected (Zhang, *et al*; 2012).

Ex-panders

Ex-pander, in general, operates in a reverse process of the same type compressor. Various types of compressors are used in a wide range of applications, from fridges to rocket engines. These compressors have significant impacts on the prototypes of ex-panders. For compression and expansion, one is a reverse process of another, so key principles in design are shared between these two machines. Positive displacement machine mainly includes reciprocating type and rotary type in which screw and scroll are two of major ex pander types. In addition, dynamic machine is majorly divided into axial type and radial expanded type. The positive displacement ex-panders are operated in an intermittent mode which is cyclic in nature. Conversely, dynamic ex-panders are operated continuously without interruption of the flow at any point in the expansion.

Air Reservoirs

Large volume air reservoir is required for large scale CAES systems, so fabricating large scale container is a key factor. This is why the current operational CAES plant use underground caverns for storage, in particular, salt caverns. From recent research, suitable geological formations include underground salt layers, underground hard rock layers, and underground porous rock layers. In Table 2, the capital cost of an air reservoir for various storage media and plant configurations are listed (Venkataramani, G. *et al*; 2016.). The cost is related to the types of storage (containers/caverns), power rating and the duration of storage. Therefore, the cost of power related components such as turbine, expander etc. is listed as \$/unit power and the cost of storage components such as underground caverns and over ground cylinders is related to their capacity and listed as \$/unit energy stored. At present, the two commercial CAES plants both adopt underground salt caverns as air

storage reservoirs, with storage capacities of 310,000m³ (Huntorf) and 560,000m³(McIntosh), respectively. In the formation and maintenance of salt caverns, some challenges are presented such as rat holes, the damage caused by small animals, the treatment of salt water, etc. (Greenblatt, J.B. *et al*, 2007, Pei, P.; 2015).

Conclusion

The review of compressed air energy storage technology for renewable energy storage in the Sudan-Sahelian zone of Nigeria, has been successfully conducted. A potential estimate of wind speeds for 10 selected sites in Nigeria render the speed between 3.6 m/s to 5.4 m/s. this results was compared with the result obtained from calculated wind speed using climate Model Mainz, gives a discrepancy of -4.3% to 4.1%, which lies within the acceptable limit of error as presented in table 2.above. Compressed Air Energy Storage (CAES), has been having low energy efficiency, because during compression of air, some energy is lost due to heat generated during compression, which cannot be fully recovered. However, .this review revealed that Compressed Air Energy Storage has gained substantial worldwide attention in recent years because of its low-cost and high-consistency in the large-scale energy storage systems.

Recommendations

- Recommended for further comprehensive research to explore more
- The government should take the advantage of the abundance of wind/solar energies in the Sudano-Sahelian region of the country to generate electric power for the zone and the country at large.
- Investors are also advice to come and invest in renewable energy generation and take the advantage of CAES as the medium to store the energy.

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Conflict of Interest by Authors:

The authors declare **no** conflict of interest.

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