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Small-Scale Energy Generation for Remote Rural Areas using Solar-Powered Compressed Air Storage System

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ORIGINAL RESEARCH

Abstract- Energy reach in the rural areas is still of major concern today especially in developing nations. Small-scale energy generation with stored compressed air is the focus of this work towards solving the energy deficit in remote rural environments through renewable sources. The method involves an experimental setup that harnessed energy from the sun through solar PV for isothermal compression and expansion of an air storage system to gain the advantages of low cost, longevity, and environmental friendliness of air storage in small scale electrical power generators. Results from a small, scalable, artificial air storage system of 360m^3 show that one charge results in approximate temperature loss of 29^{o}C for compression and 10^{o}C for expansion (in a single cycle). A pressure charge of about 6bars from a compressor speed of 300rpm was also obtained and was able to maintain a constant alternator speed of 2500rpm on no load to produce electricity at 230Vac during expansion. When advanced and standardized, the air storage could provide a medium for cheap electrical energy storage for small scale renewable sources and a means for electrical energy availability in remote rural environments.

Keywords- Compressed Air, Electricity, Renewable Energy, Generator, Low-cost

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1 INTRODUCTION

Challenges of Electrical Energy (EE) transmission to most remote rural areas in developing countries are enormous (Daniel, 2017; Michael and Uko, 2012; Xueli *et al*, 2013), leading to over dependence on fossil fuel electric generators in such areas. The operation of these generators poses number of challenges such as fuel supplies and maintenance delays (Elusakin *et al*, 2014). Recently, several nations and organizations are employing the use of Renewable Energy (RE) sources, solar and wind especially, in meeting the need of these rural areas (Samuel and Getachew, 2019) and in supply of remote equipment that are out of reach to main electrical power supply sources.

RE sources are attracting enormous attention though intermittent and unstable in nature and require the use of Electrical Energy Storage (EES) systems to help stabilize and maintain constant supply (Evelina and Malin, 2018; Altin, 2016; Salisu *et al*, 2020). Application of medium to large scale EES is financially demanding, putting more strain to the deployment of RE systems in remote areas. EESs are of different technologies and can be weighed for application in certain characteristics such as operational duration and cost (Martin *et al*, 2011; Henok *et al*, 2020). These storage technologies in the form of Pumped Hydro Energy Storage (PHES), Flywheel, Fuel-cell, Compressed Air Energy Storage (CAES), Supper Capacitors, superconducting magnetic energy storage (SMES) and Chemical Batteries are suited for specific demands.

Since 1800 AD when the first voltaic pile was discovered (Chukwuka and Folly, 2012), the chemical battery has been the most applied and available storage system for micro-scale EE generation. These chemical devices are quite bulky, expensive and have short operational lifetime. These limit their use and discourage intending applicants from deploying micro-scale RE systems even in private homes. Among storage technologies, PHES has attained the highest international penetration for large-scale applications due to good efficiency and high storage capacity (Huanran *et al*, 2013; Yang *et al*, 2013; Kendall *et al*, 2020). However, the CAES is a developed technology and can be argued to have attained a maturity level being utilized in large-scale systems over 50years (Chen *et al*, 2021). At the moment, due to technology advancement, it has attained efficiency and capital cost close to that of PHES (Wang *et al*, 2017; Hossein *et al*, 2013). This research in solar application centred on CAES systems since they are more scalable than PHES.

2 ELECTRICAL ENERGY STORAGE METHODS

EES systems have a range of applications, including providing power to autos, portable devices, and stationary energy resources, such as in off-grid supply systems. They are currently emerging as a crucial component of the answer to enhance access to electricity (IRENA, 2017). There are several of these EES systems in use at present and more are being developed and advanced with emerging technologies. EES systems can be conveniently grouped into three categories as matured, developed, and developing technologies.

2.1 MATURED EES TECHNOLOGIES

Since they have been in use for so long and commercially successful, these EES technologies, which include PHES and Lead-Acid Battery Storage (LABS) (ThuTrang et al, 2017). They are adjudged as technologies with appreciable capacity and cost (Ziegler *et al*, 2019) for

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Section B- ELECTRICAL/ COMPUTER ENGINEERING & RELATED SCIENCES
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electrical power systems applications. PHES, for instance, has over 200units and ~160GW installed capacity globally (IRENA, 2020). The major limitation of PHES is problem of appropriate site and high cost of construction. Contrarily, LABS have been widely used in grid power networks and are very scalable to fit a variety of power platforms in off-grid and behind-the-meter applications. More recently, LABS have been created with high charge performance suitable for automotive applications. However, the energy capacity cost of storage for LABS is high compared to PHES, which is occasioned by degradation over time and their subsequent replacement (Micah *et al*, 2019).

2.2 DEVELOPED EES TECHNOLOGIES

Developed EES are storage technologies like CAES, Flywheel, Li-ion battery that have been practically proven but are still being investigated for reliability in certain applications. With some technologies nearing maturity, their application window is wide and will provide a robust storage system. With its first large scale use in Huntorf, Germany in 1978 (Boicea, 2014, Eugene,2016), CAES is second most available storage technology commercially installed aside PHES (Hussien *et al*, 2015). Because CAES is scalable, they are attracting attention towards the development of Small-scale CAES (SCAES) for power applications (Xing *et al*, 2014). Deployment of SCAES system is thought to provide long storage life-span, low supply cost compared to batteries, and no site restrictions (Hussien *et al*, 2015, Castellani *et at*, 2018). Also, flywheel systems advantages include high power, long cycle life, high efficiency of about 90%—95% (Mustafa and Keith, 2017), high durability, and its environmental friendliness. It however has serious limitation in its high self-discharge rate of about 5%—20% per hour (Altin, 2016). Li-ion batteries have long life cycle, energy density of ~ (150 to 250) Wh/kg about more than 5 times that of LABS, efficiency of ~ (95 to 99%) (Juan *et al*, 2017) does not have memory effect and lower degradation at partial charge. At the present, the cost of Li-ion batteries is still considered high, which is the major cause of its limited usage in behind-the-meter stationary application.

2.3 DEVELOPING TECHNOLOGIES

Storage technologies that are technically feasible but not yet economically available include solar fuel, fuel cells, cryogenic energy storage, metal air batteries.

3 SOLAR CHARGED CAES SYSTEM DESCRIPTION AND METHOD

SCAES systems are modelled in replication of their large CAES counterparts but with some simplicity that reflect their fitness into their operational environment and method of activation. In this approach, the modelled system can be used near the living environment and self-activated. As expected, the system comprises primarily of an air compressor, an air storage unit, and an air turbine. A DC motor that turns dc voltage from a solar PV array into mechanical rotation powers the compressor. The storage, connected to compressor's output, is pressured with air at room temperature. Following expansion through the turbine and exhaust back into the atmosphere, the pressurized air is released. However, as shown in Figure 1, the turbine that transforms air pressure into mechanical rotation is connected to an electric generator to generate electricity.

To understand the system's operation, a power flow model from the solar PV input to the generator output was considered as shown in Figure 2. According to ideal representation, the total energy used in pumping air pressure into the storage tank should equal the generated energy by the output air pressure. However, there are points of energy loss within the system that make it difficult to realize this balance and must be well managed to get close to such ideal situation. With an assumed complete daily cycle of compression and expansion phases, the system is expected to produce a steady electrical energy output at certain efficiency when fully charged. This efficiency specifies how well the system uses its energy supply for output production. Equations (1) and (2), give the energy absorbed by the compressor and that produced by the turbine (Castellani et al, 2018).

$$W_{comp} = m_{air}\ x\ \Delta h_{comp} \tag{1}$$

$$W_{exp} = m_{air}\ x\ \Delta h_{exp} \tag{2}$$

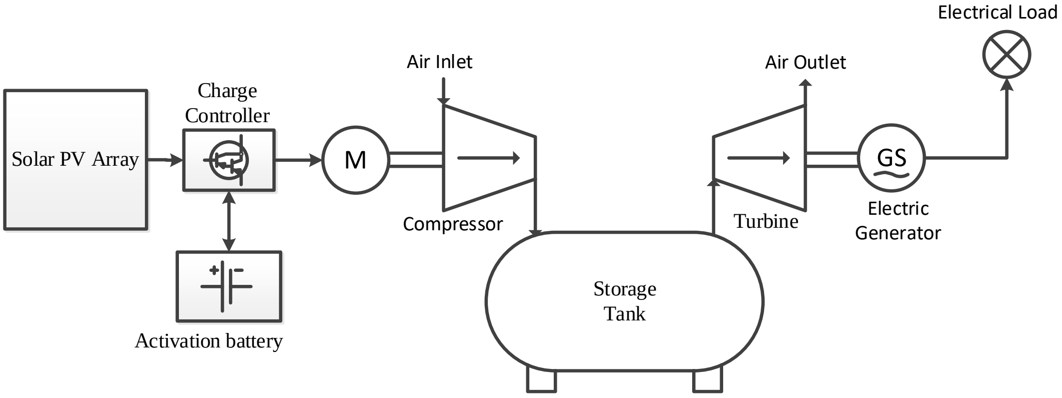

Fig. 1: Small-scale solar-air electric power generation model

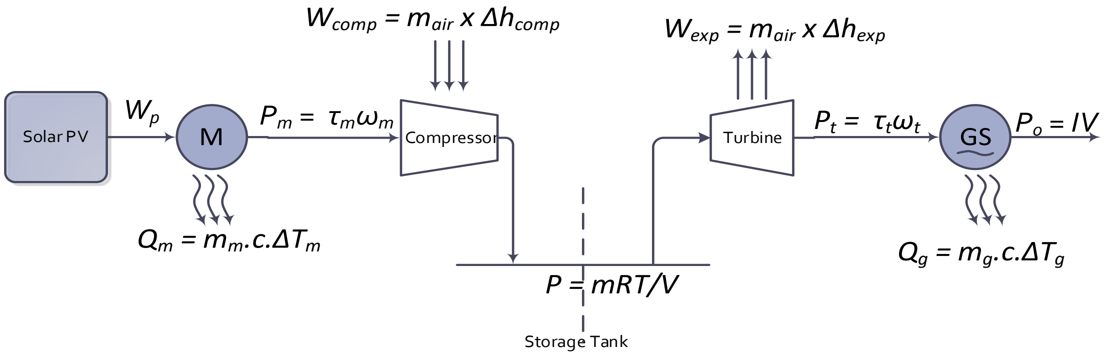

Fig. 2: The micro-scale Solar-Air generator power model

The compression to expansion electrical efficiency of the storage system can therefore be found by equation (3) as:

$$\eta = \frac{W_{exp}}{W_{comp}} \tag{3}$$

To power the electrical load, however, the turbine output is applied to a synchronous generator while the compressor is driven by a dc motor. These devices are sources of energy loss due mainly to heating as shown in Figure 2 and indicated in equations (4) and (5), and used in determination of system's final efficiency.

The input and output pressure end efficiencies are estimated separately using the storage as the isolation point, and they are then combined at the compression to expansion efficiency point to determine the overall efficiency as in equations (6) to (8).

$$Q_m = m_m c \Delta T_m \tag{4}$$

$$Q_g = m_g c \Delta T_g \tag{5}$$

$$W_{comp} = \eta_c\ x\ W_p \tag{6}$$

$$W_{exp} = \frac{P_o}{\eta_e} \tag{7}$$

Substituting (6) and (7) into equation (3) therefore, give the entire system's efficiency as:

$$\eta = \frac{P_o}{\eta_c \eta_e W_p} \tag{8}$$

Nomenclature

Symbol	Description	Unit
W	Energy	kJ
Q	Heat energy	kJ
m	Mass	kg
ΔT	Change in temperature	K
P_o	Output Power	W
τ	Torque	Nm
ω	Speed	rpm
c	Specific heat capacity	kJ kg^{-1} K^{-1}
W_p	PV power	W
R	Specific gas constant	Constant
T	Temperature	K
V	Volume	m^3

3.1 METHOD

Using the air storage model described in (Uzedhe and Akinloye, 2020), an experimental SCAES was setup to examine the process. The setup is in three sections: solar energy conversion, air storage, and air pressure converted to electricity. As shown in Figure 3, energy from the solar PV system drives a DC motor. The dc motor is coupled with belt to a compressor to pump air into three storage cylinders connected in parallel through some control valves and tubing. The pressurized air is then expanded through a rotary vane air motor which serves as turbine to drive an alternator. The compression and expansion heat losses are free to the surrounding environment and are not controlled or recovered back. These isothermal heat losses are however measured in temperature variations within the operational period. To apply operational measures of data collection from the setup, the system was allowed to compress air in a short period of time and the compressor short down. The air pressure in the storage was then measured and monitored for some minutes and then expanded. The compressor and expander temperatures, compressor speed, alternator speed, and alternator output voltage were recorded.

3.2 COMPONENTS AND SYSTEM SETUP

The set-up is as shown in Figure 3 consisting of components such as solar PV array, DC motor, compressor, storage tank, air motor as turbine and electric generator.

a. Solar PV unit: this unit is an array of six number of 250W each amorphous PV panels, a PWM charge controller and a 24V/100Ah activation battery. While the PV array generates the required electrical power to continuously run the system, charge controller help regulates the panel PV output to the motor. The battery is used to activate the DC motor by ensuring adequate activation current is available to drive the motor at start up.

b. DC Motor: the dc motor serves as the prime mover for the compression stage. It helps to convert the DC electrical energy from the PV array to a mechanical power for driving the compressor. The motor used is a 24V/30Ah system, capable of delivering a torque of 60Nm at a speed of 2500rpm.

c. Compressor: the compressor used is an 8bar, 1000rpm compression with a compression ratio of 5:1.

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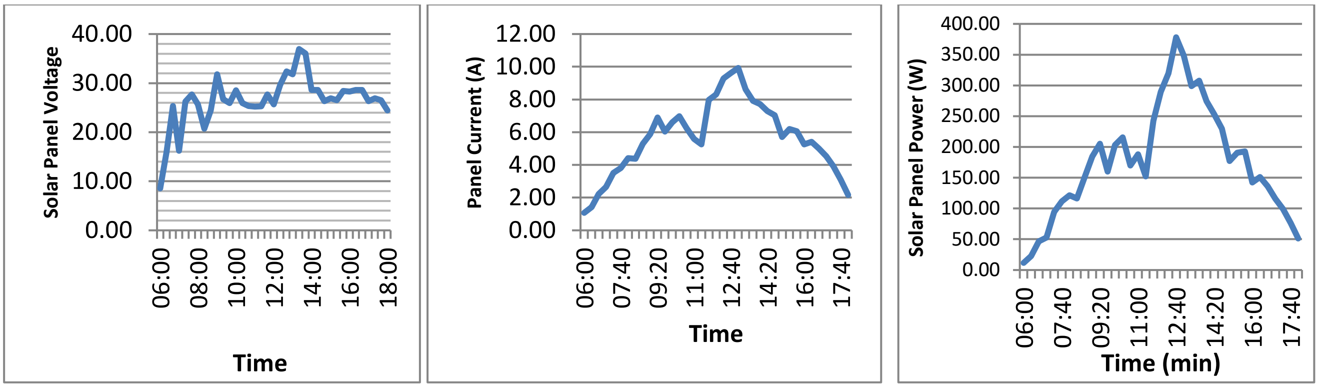
Fig. 3: Experimental SCAES setup



(a) (b) (c)

Fig. 4: (a) Average daily generated panel voltage (b) Average daily panel current (c) Average daily generated electrical power

d. Storage tank: the storage tank consists of three cylinders of 50kg each providing a total air volume of approximately $120m^3$.These cylinders are connected in parallel between the inlet and outlet air piping. The cylinders are not however lagged but are shaded and used in ambient temperature.

e. *Air turbine*: the air turbine is a rotary vane air motor from Hongxin with operational speed of 3000rpm, output torque of 4.1Nm and input air consumption of 78CFM.

f. *Electric generator*: the generator used is a single-phase 2kVA, two (2) pole synchronous generator.

4 RESULTS AND DISCUSSION

The results are presented in sections accordingly.

4.1 PV ENERGY

The kind of PV output current and voltage generated significantly impact solar subsystem's daily continuous energy production. This is highly reliant on the daily and seasonal sun radiation in the application region. The PV output characteristics of the system configuration used at Effurun, a city in Nigeria's Niger Delta, are shown in Figures 4a, 4b, and 4c. The prototype setup's PV daily average voltage and current are shown in Figures 4a and 4b, respectively. The PV daily average power output is shown in Figure 4c as a representation of the PV current and voltage.

4.2 ENERGY LOSS

To identify potential points of energy loss through the system, thermal behaviour at various stages was considered. Energy loss reduces system efficiency as output power tends to be less relative to design effort. These losses may occur in different forms more notably in heat and mechanical frictional forces. Frictional losses can be reduced by design and are usually more minimal compared to heat energy losses. However, both heat and frictional losses can lead to each other in rotational parts creating a resultant combination with grave losses and subsequent damage. Figures 5a and 5b indicate the energy losses in expansion and compression respectively. These losses where however obtained as a measure of change in temperature in the component parts. Figure 6 compare compression and expansion loses and clearly shows that more energy loses takes place at compression.

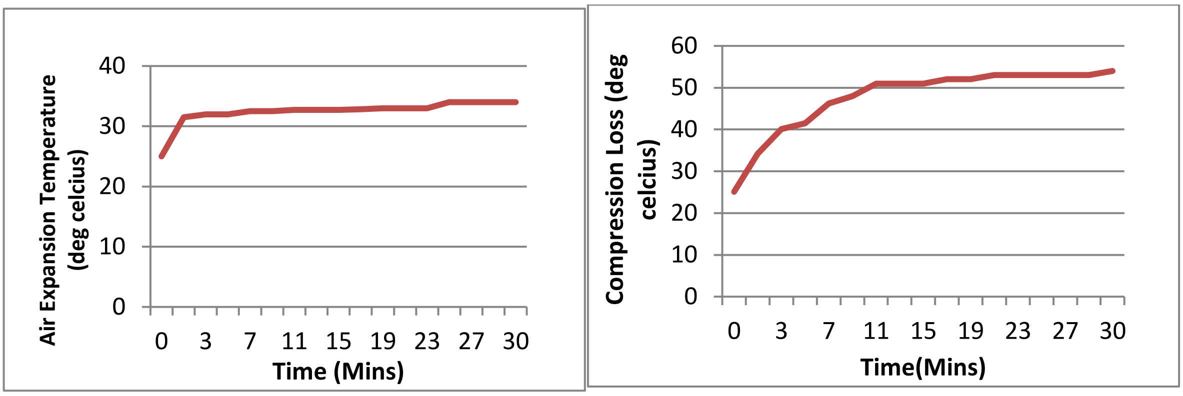


Fig. 5: Energy loss (a) in expansion (b) compression over time due to rise in temperature

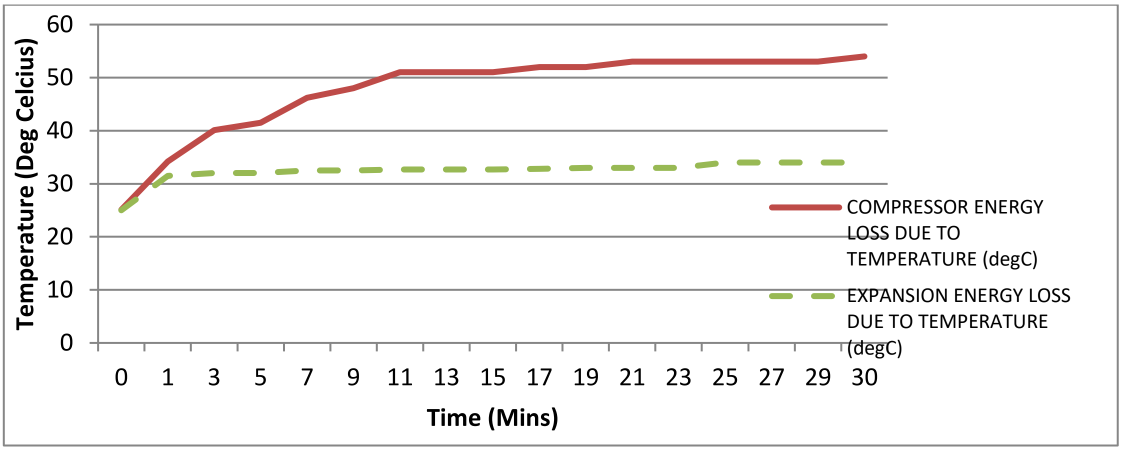


Fig. 6: Comparing compression and expansion loses

4.3 POWER CAPABILITY

The system pressure build-up in the cylinder, as shown in Figure 7, clearly sustains its operation especially during charging. A faster charge provides enough pressure for motor propulsion at the shortest time and still maintains pressure growth in storage. The charging rate also has a direct relation to drive components power. To provide and stabilize the output voltage, the various drive components must be kept at certain rotating speed. A comparative speed of the drive components used is indicated in Figure 8 and shows how low compression speed maintain constant high alternator speed.

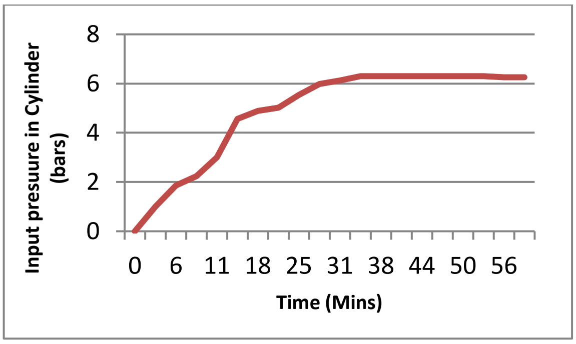


Fig. 7: Pressure in cylinder during charging

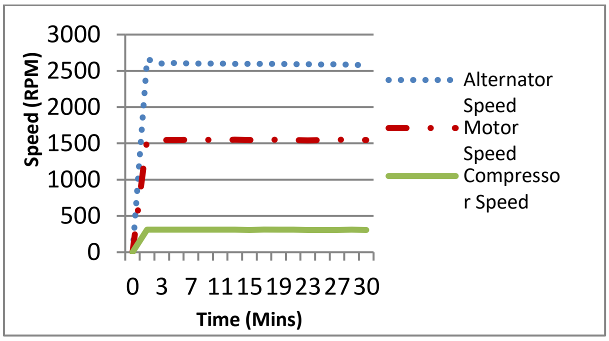


Fig. 8: Comparative operating speed of system drivers

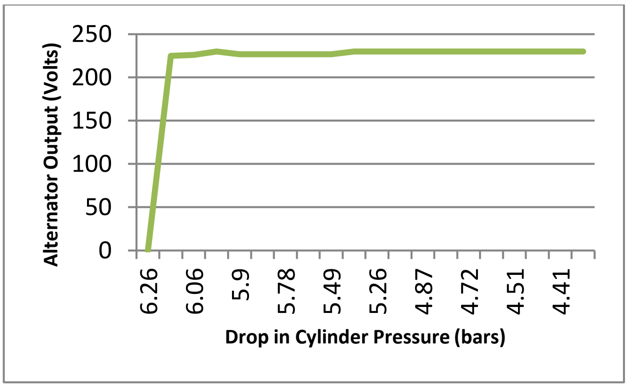


Fig. 9: System output voltage with pressure drop

The system output voltage is plotted in Figure 9 against the decrease in cylinder pressure during discharge. Within the period of measurement, it was discovered that

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the system's output voltage was maintained at around 230V when fully charged to when cylinder pressure drops 1.5bars. This indicates that building up higher in storage will result to a more sustainable system with higher autonomy.

5 CONCLUSION

The use of air storage systems in small-scale compressed air energy generation in renewable energy solutions can address the major difficulty of energy delivery in remote rural locations, particularly in developing nations. Though there are potential areas of energy loss due to heat that may result to low efficiency as observed, this work showed that electrical energy can be generated from pressurized air in man-made storages. With some advancement of the technique applied through energy recovery such as in adiabatic processes, air storage can be made readily available for low-cost remote applications.

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REFERENCES

Altin Necmi (2016) "Energy Storage Systems and Power System Stability", *3rd International Smart Grid Workshop and Certificate Program (ISGWCP)*, Istanbul, Turkey, March 21-25, 2016.

Boicea V.A. (2014), "Energy Storage Technologies: The Past and the Present" Proceedings of IEEE, Vol. 102, No. 11, November 2014, pp. 1777- 1794.

Castellani Beatrice, Morini Elena, Nastasi Benedetto, Nicolini Andrea and Rossi Federico (2018), "Small-Scale Compressed Air Energy Storage Application for Renewable Energy Integration in a Listed Building", *Energies*, Vol. 11, pp. 1921; doi:10.3390/en11071921

Castellani, B., Morini, E., Nastasi, B., Nicolini, A., & Rossi, F. (2018), "Small scale Compressed Air Energy Storage application for renewable energy integration in a listed building", Energies,11(7), https://doi.org/10.3390/en11071921

Chen Laijun, Zheng Tianwen, Mei Shengwei, Xue Xiaodai, Liu Binhui, Lu Qiang (2016) "Review and prospect of compressed air energy storage system", Retrieved from https://link.springer.com/article/101007/s40565-016-0240-5, Accessed March 11, 2021.

Chukwuka C. and Folly K A, (2012) "Batteries and Super-capacitors", *IEEE PES Power Africa 2012 and Exposition*, Johannesburg, South Africa.

Daniel Champier (2017), "Thermoelectric generators: A review of applications", Energy Conversion and Management 140 pp. 167–181.

Elusakin Julius E., Ajide O. Olufemi and Diji J. Chuks (2014), "Challenges of sustaining off-grid power generation in Nigeria rural communities", *African Journal of Engineering Research*, Vol. 2, No. 2. pp 51 – 57.

Eugene Freeman, Davide Uccello, and Frank Barnes (2016), "Energy storage for electrical systems in the USA", AIMS Energy, Volume 4, Issue 6, pp856 – 875. Doi: 10.3934/energy.2016.5.856

Evelina Steen and Malin Torestam (2018) "Compressed Air Energy Storage Process review and case study of small scale compressed air energy storage aimed at residential buildings", Degree Project in Technology, KTH Royal Institute of Technology School of Architecture and the Built Environment, *Stockholm, Sweden,*

Henok Ayele Behabtu, Maarten Messagie, Thierry Coosemans, Maitane Berecibar, Kinde Anlay Fante, Abraham Alem Kebede and Joeri Van Mierlo (2020) "A Review of Energy Storage Technologies' Application Potentials in Renewable Energy Sources Grid Integration", *Sustainability* Vol. 12, 10511; doi:10.3390/su122410511

Hossein Safaei, David W. Keith, Ronald J. Hugo (2013) "Compressed air energy storage (CAES) with compressors distributed at heat loads to enable waste heat utilization", *Applied Energy* Vol. 103 pp. 165–179.

Huanran Wang, Liqin Wang, Xiabing Wang and Erren Yao (2013) "A Novel Pumped Hydro Combined with Compressed Air Energy Storage System", *Energies*, Vol. 6, pp. 1554 – 1567; Doi: 10.3390/en6031554.

Hussien Ibrahim, Karim Belmokhtar and Mazen Ghandour (2015), "Investigation of Usage of Compressed Air Energy Storage or Power Generation System Improving – Application in a Microgrid Integrating Wind Energy", 9th International Renewable Energy Storage Conference, IRES 2015, Energy Procedia 73 (2015) 305 – 316.

IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi.

IRENA (2020), Innovation landscape brief: Innovative operation of pumped hydropower storage, International Renewable Energy Agency, Abu Dhabi.

Juan Arteaga, Hamidreza Zareipour & Venkataraman Thangadurai (2017), "Overview of Lithium-Ion Grid-Scale Energy Storage Systems", Curr Sustainable Renewable Energy Rep, Springer International Publishing AG 2017, DOI 10.1007/s40518-017-0086-0.

Kendall Mongird, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, Vincent Sprenkle, Richard Baxter (2020) "Grid Energy Storage Technology Cost and Performance Assessment", *Energy Storage Grand Challenge Cost and Performance Assessment 2020, Technical Report Publication* No. DOE/PA-0204December 2020, US Department of Energy.

Martín San J.I., Zamora I., Martín San J.J., Aperribay V., Eguía P., (2011) "Energy Storage Technologies for Electric Applications", *European Association for the Development of Renewable Energies, Environment and Power Quality, International Conference on Renewable Energies and Power Quality (ICREPQ'11)* Las Palmas de Gran Canaria (Spain).

Micah S. Ziegler, Joshua M. Mueller, Goncalo D. Pereira, Juhyun Song, Marco Ferrara, Yet-Ming Chiang, and Jessika E. Trancik (2019), "Storage Requirements and Costs of Shaping Renewable Energy Toward Grid Decarbonization" Joule 3, 2134–2153, September 18, 2019, Elsevier Inc. https://doi.org/10.1016/j.joule.2019.06.012.

Michael U. Onuu and Uko Ofe (2012), "Towards Solving the Problem of Transmission and Distribution of Electric Power in Nigeria via Superconductor Power Cables", *Global Journal of Pure and Applied Sciences*, Vol. 18, No. 3&4, pp. 169-177. DOI: http://dx.doi.org/10.4314/gjpas.v18i3-4.8

Mustafa E. Amiryar and Keith R. Pullen (2017), "A Review of Flywheel Energy Storage System Technologies and Their Applications", Appl. Sci. 2017, 7, 286; DOI:10.3390/app7030286. www.mdpi.com/journal/applsci.

Salisu Aliyu, Aminu S. Zakari, Muhammad Isma'il and Mohammed A. Ahmed (2020), "An Artificial Neural Network Model for Estimating Daily Solar Radiation in Northwest Nigeria", FUOYE Journal of Engineering and Technology (FUOYEJET), Vol. 5, Issue 2, September 2020. http://dx.doi.org/10.46792/fuoyejet.v5i2.563

Samuel L. Tesema1, Getachew Bekele (2019), "High Wind Power Penetration Large-Scale Hybrid Renewable Energy System Design for Remote Off-Grid Application", *Journal of Power and Energy Engineering*, Vol. 7, pp. 11-30.

Thu-Trang Nguyen, Viktoria Martin, Anders Malmquist, and Carlos A.S. Silva (2017), "A review on technology maturity of small-scale energy storage technologies", Renew. Energy Environ. Sustain. 2, 36 (2017).

Uzedhe Godwin O. and Akinloye Benjamine O. (2020) "Controlled Solar-Pneumatic Energy Storage System for Green Power Generation", FUPRE Journal of Scientific and Industrial Research, Vol.4, (1), January 2020.

Wang J., Kunpeng L, Lan M., Jihong W., Mark D., Shihong M., Jian L and Dan W., (2017) "Overview of Compressed Air Energy Storage and Technology Development", *Energies*, Vol. 10, pp. 987 - 999; doi:10.3390/en10070991.

Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke, and Christopher Krupke (2014), "Overview of current development in compressed air energy storage technology", International Conference on Sustainability in Energy and Buildings, SEB-14, Energy Procedia 62 (2014) 609 – 611.

Xueli Wu, Xiuyuan Yang, Hong Shen, Qinyong Zhou (2013) "Research on the Long-distance Transmission", *Energy and Power Engineering*, Vol. 5, pp. 1293-1297.

Yang Gu, James McCalley, Ming Ni and Rui Bo (2013) "Economic Modeling of Compressed Air Energy Storage", *Energies*, Vol. *6*, pp. 2221-2241; doi:10.3390/en6042221