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Investigation of Usage of Compressed Air Energy Storage for Power Generation System Improving - Application in a Microgrid Integrating Wind Energy

Hussein Ibrahim^{a*}, Karim Belmokhtar^a, Mazen Ghandour^b^a*TechnoCentre éolien, 70 rue Bolduc, Gaspé, QC, G4X 1G2, Canada*^b*Lebanese University, Engineering Faculty, Beirut, Lebanon*

Abstract

Compressed air energy storage (CAES) is one of the most promising mature electrical energy storage technologies. CAES in combination with renewable energy generators connected to the main grid or installed at isolated loads (remote areas for example) are a viable alternative to others energy storage technologies. Indeed, because of the advantage of fast response, high economic performance and small environmental impacts, CAES has an extensive application prospect. In this paper, recent technological advances in CAES are examined. This review includes an examination of the different topologies of power systems integrating CAES and wind turbines (as power source), an overview of air and thermal storage systems, and an examination of CAES in a distributed application such as wind-diesel compressed air hybrid system used to supply the remote areas.

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Keywords: Energy storage, compressed air energy storage, thermal storage, wind energy, wind-diesel hybrid systems.

1. Introduction

An increasing recourse to renewable energies (RE) is one of the key solutions to address the current resource and environmental concerns related to the world energy supply [1]. Because of the distributed and intermittent nature of

* Corresponding author. Tel.: +1-418-368-6162#238; fax: +1-418-368-4315
E-mail address: hibrahim@eolien.qc.ca

several of them (solar, wind), an efficient and economically viable exploitation of renewable energies relies on the use of energy storage systems (ESS) [2]. ESS refers to a technology process, in which electrical energy is converted into different forms of energy suitable for storage and the energy stored can be converted into high quality electrical energy when needed [3]. Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources and to be used at times of high demand, high generation cost or when no other generation means is available [4]. ESS in conjunction with RE can provide some environmental, technical [3], and financial benefits [5] to a power system. Indeed, ESS provide, in real time, the balance between production and consumption and improves the management and the reliability of the grid [6]. Furthermore, the ESS increase the penetration rate of renewable resources and the quality of the supplied energy by better controlling frequency and voltage. Different types of storage techniques, based on various physical principles, are theoretically and operationally available to remedy the RE fluctuations and to match an application. Each of these technologies is well suited for a specific power or energy range. Flywheel, hydrogen, pumped hydro, compressed air energy storage (CAES), capacitors, batteries, and superconducting magnetic energy storage (SMES), are some examples of available energy storage systems [7]. Among all the ESS, CAES are considered as having reached technical maturity. CAES is a large-scale energy storage technology with over 45 years [4] in operation. Due to recent technological and thermodynamic advancements, it has the potential to reach efficiencies and capital costs comparable to pumped hydro storage (PHS) [8], which is currently the storage technology with highest international penetration (99% of installed ESS [9]). On the other hand, CAES is unique among ESS technologies, it is modular and transportable, readily adaptable to co-generation applications; and are both flexible in bulk power management and grid support applications [10].

2. Various options of uses of compressed air energy storage in electrical power generation

Compressed air energy storage systems have been proposed from many years and have been applied in the middle and high power range, as well as in electrical power generation and transportation applications. More recently, a thermal and compressed air storage system (THCAS) has been presented in objective to improve the overall efficiency of the system by recuperation of compression heat and using it later before discharge the compressed air into production system (air or gas turbine, reciprocating machine, etc.). While conventional CAES-systems use additional combustion in order to reach the normal operation conditions of the turbine, THCAS systems need a permanent heating power for maintaining the temperature of the thermal storage device. Several categories of technologies are being developed. The first one is mainly characterized by the storage of the compression heat, either in a separated thermal storage unit like in the case of the Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system, or in the high-pressure vessel together with the compressed air; this is the case of the Uncooled Compressed Air Storage. The second family tries to implement isothermal processes by exporting (and latter importing) the compression heat to the surroundings through various heat exchange techniques. This is the case of the pneumatic storage system. The third family investigate the use of compressed air in hybridization with diesel generator used with wind power plant to supply remote areas. These different modern compressed-air-based storage systems for power generation will be briefly described in the following sections.

2.1. Conventional or diabatic compressed air energy storage (D-CAES) systems

The working process of a conventional large-scale CAES plant can be considered to have the similarities to that of a gas turbine based power plant except that the process of CAES decouples the compression and expansion cycles of a gas turbine into two separate processes occurring at different time [11]. This functional separation of the compression cycle from the combustion cycle allows a CAES plant to generate three times more energy with the same quantity of fuel compared to simple cycle natural gas power plant [2]. Both the Huntorf and the McIntosh plants were implemented through the conventional CAES technology. The lower-cost energy from off-peak electricity, or excess RE, is used to compress air to 44-70 bar [6]. The compressed air stream is cooled to near ambient via intercoolers and stored in an underground caverns. During peak periods (generation phase), or to support intermittent RE, the pre-compressed air from the storage cavern is preheated through a heat recuperator, then

mixed with natural gas or oil and burned in a combustion chamber ($\sim 550^{\circ}\text{C}$) [9] and then expanded through a multistage coupled turbine-generator. The schematic diagram (process and energy flow) of the McIntosh plant with energy and heat inputs for a 1.00kWh is presented in Figure 1 [10], [12]. Two conventional CAES plants are in planning: Norton, Ohio (2,700MW) (on development) and PG&E, California (300MW) that is scheduled to issue an RFP in 2015 [13].

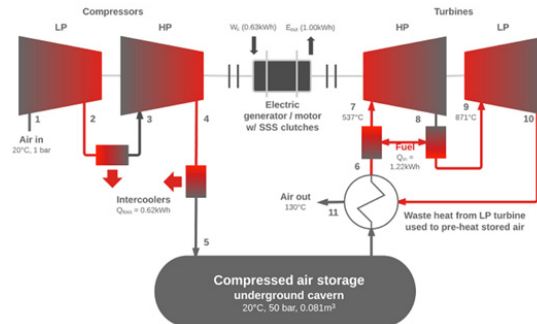


Figure 1: Principle of CAES system: Schematic of the McIntosh plant in Alabama, USA [2], [10], [14]

2.2. Hybrid compressed air and thermal storage systems

In order to avoid the emissions and fuel dependence of classical CAES, alternative, fuel-free, compressed-air-based storage systems have been investigated, with the main idea of storing the heat generated during compression and later use it to reheat the high pressure air before expansion [2], [15]. In this concept of unfired or adiabatic CAES, there are many possible ways of storing the necessary expansion-heat that have led to the different hybrid thermal and compressed air storage systems presented in the next paragraphs.

2.2.1. Advanced adiabatic - compressed air energy storage (AA-CAES)

The AA-CAES concept has been implemented in the frame of an ongoing European project aims at enhancing the classical CAES so as to develop a pure or non-hybrid storage system based on compressed air [16]. The basic idea of the adiabatic AA-CAES concept is the use of heat storage as the central element of the plant, as shown in Figure 2. This implies that the heat needed for the expansion process is recovered from the compression and stored in a Thermal Energy Storage (TES) unit for the time interval of the charge-discharge cycle [2]. This reduces, or completely eliminates, the need for a combustor [10]. During charging, the compressed air must be cooled to the cavern inlet temperature which is about 50°C for salt caverns. During discharge, the compressed air is heated up to almost the compressor outlet temperature at high heat extraction rates. To reach high pressure with reasonable temperature, the compression and heat storage systems can be divided into two or more stages.

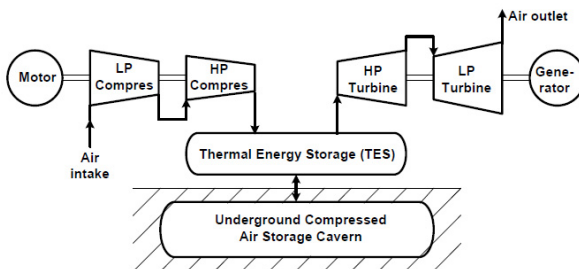


Figure 2: One-stage arrangement of an AA-CAES system [2]

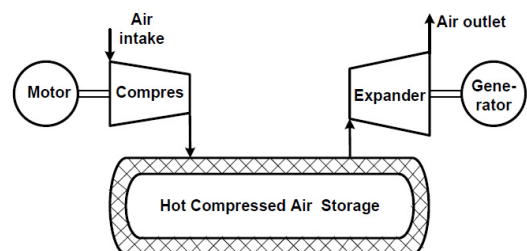


Figure 3: Schematic diagram of the uncooled CAES [2]

There is currently one AA-CAES project in planning stage set for commissioning 2020: Project ADELE, Germany (360MW). There are some technical challenges facing the further development of AA-CAES, including the design of cost-effective thermal energy storage to absorb and store energy with minimal thermal losses at temperatures up to 600°C [10]; and new HP compressor designs will be required to handle the high compression temperatures [17].

2.2.2. Uncooled compressed air energy storage

To avoid the difficulty of realizing a cheap and high performance thermal storage unit, needed in the other hybrid thermal and compressed air storage systems [2], a system where the compression heat is stored together with the compressed air in an isolated vessel has been investigated at the Technical University of Clausthal-Germany [18]. The principle of such a system is shown in Figure 3. If the system was to really achieve adiabatic processes, the thermodynamic energy efficiency would be 100%. The unavoidable heat-losses due to the non-ideal insulation of the storage vessel limit the storage time; hence, this technology would be mainly dedicated to bridging or short-time storage applications [2]. In addition, to handle the wide temperature variation range related to the adiabatic processes, the system requires costly air motors and compressors with particular design. The pressure range must also remain very low to limit the maximum temperature [16].

2.2.3. Hybrid thermal and compressed air energy storage (TACAS)

The Thermal and Compressed Air Storage (TACAS) is essentially a standalone and smaller version of classical CAES, with the main following differences which can be seen on the principle diagram of Figure 4[2]:

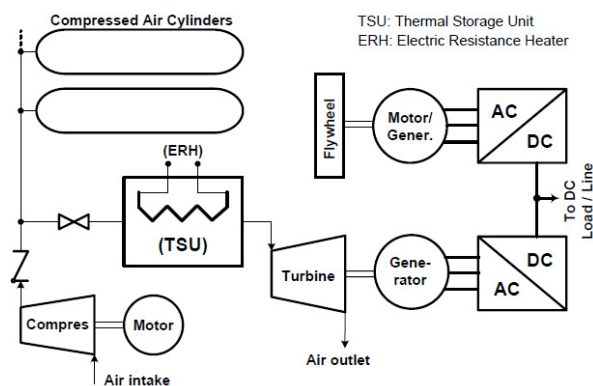


Figure 4: Principle of the hybrid thermal and CAES system [2]

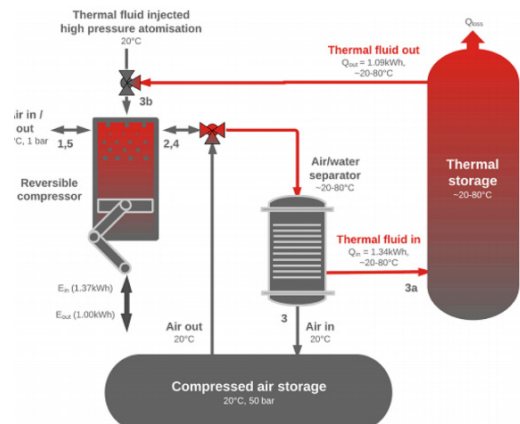


Figure 5: Process overview and energy flow of I-CAES [10]

- The TACAS system uses conventional high pressure cylinders to store the compressed air;
- The needed expansion heat is provided by a steel Thermal Storage Unit (TSU). The TSU is brought to full operating temperature by industrial electric heating resistances, fed with part of the low-cost utility power to be stored.
- The TACAS system uses a low-cost flywheel to maintain power quality and to provide a few seconds of bridging power during the operation of the system.

2.3. Isothermal Compressed Air Energy Storage

Isothermal CAES (I-CAES) attempts to achieve near-isothermal compression in situ, thus avoiding external heat exchangers to compress/expand air [10]. This yields improved system efficiencies (~70%-80%) [12], provides fuel-

free operation, and reduces thermal stress on equipment. Three patented I-CAES technologies under development include: the injection of liquid (water/oil) into a reciprocating piston cylinder during air compression, or the bubbling of air through the liquid [19]; the separation and collection of that medium into a TES reservoir; and the re-injection of the warm liquid into the cylinder during expansion (Figure 5). Current I-CAES approaches employ up to a three-stage reversible compressor/expander, with each cylinder realizing up to a 1:30 compression ratio [20] and total pressure up to 400 bars. These approaches have been realized in three partially government funded and now operational pilot scale I-CAES plants: General Compression (2MW, 500MWh 2012); SustainX (2MW, 8MWh 2013); and LightSail Energy (2MW, 8MWh 2013) [19], [21], [22].

2.4. Small-Scale Compressed Air Energy Storage

Distributed, stand-alone, microgrid, and UPS applications of CAES offer an alternative to electro-chemical battery storage. The advantages of Small-scale CAES (S-CAES) include: no siting restrictions, longer life-span and potentially lower supply cost than batteries, can be integrated with existing heat and cooling sources in a co-generation application, and can supply additional local support services, such as VAR correction [10]. Three types of application of (S-CAES) will be presented in the following sections: hydro-pneumatic energy storage systems and the use of compressed air with wind-diesel hybrid systems used to supply remote areas and microgrids.

2.4.1. Hydro-pneumatic energy storage systems

The pressure ratings and conversion efficiency of pure pneumatic conversion system remains low because of the difficulties to implement good heat exchange in the compression/expansion chambers and the important leakage and friction due to the gaseous nature of air [2]. The use of oil-hydraulic machines to circumvent these difficulties has been investigated, as they suffer less from the above problems and therefore exhibit very high conversion efficiencies. The main challenge in using this kind of machine is the oil-to-air interface. Two different ways of interfacing the two fluids in almost isothermal processes are possible and have led to the two hydro-pneumatic storage systems whose principles are depicted in Figure 6, and described in [23] and [24] under the acronym “BOP” which stands for Batteries with Oil-hydraulics and Pneumatics.

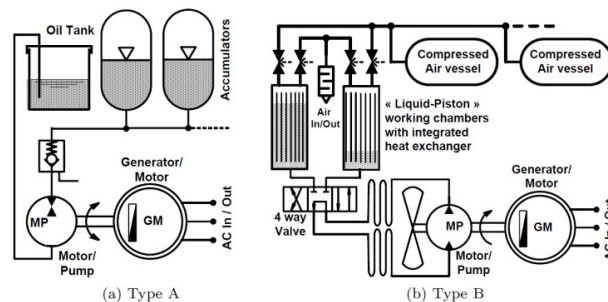


Figure 6: Schematic diagram of pneumatic storage systems with oil-hydraulic conversion [2]

The first system, Type A, is simply an extension of the well-known industrial hydro-pneumatic accumulators to large storage capacity applications [2], [16]. In these devices, there is a physical separation between air and oil, that can be a piston, a bladder or a membrane depending on the type of accumulator. The main drawback of Type A system is its low energy density due to the fixed amount of gas and the outside reservoir needed to store the compressing oil at the discharge state. The second system, Type B, is better in that respect, since it uses a substantially reduced amount of oil working in a closed circuit to compressed fresh air from outside [2]. However, it requires an oil-to-air interface which is based on the “Liquid - Piston” principle and is difficult to realize.

2.4.2. Compressed air with wind-diesel hybrid systems

Due to technical, economical and energetic advantages demonstrated by the compressed air energy storage (CAES) in hybrid systems at large scale use in the USA and Germany, we investigated in several previous work [3], [6], [25], [26], [27], [28], [29], [30], [31], [32] the use of compressed air energy storage with the hybrid wind-diesel system for medium and small scale applications (remote areas) in order to improve the exploitation of diesel generator in these sites. Indeed, the use of compressed air as an energy storage agent is well applied to both wind energy production and to diesel groups. Two topologies are developed for wind-diesel compressed air hybrid system (WDCAS) [33]:

- The medium-scale WDCAS (MSWDCAS)
- The small-scale WDCAS (SSWDCAS)

In this paper, two case studies will be presented to demonstrate the numerous advantages of CAES for hybrid wind-diesel systems

2.4.2.1. Medium scale wind-diesel-compressed air system

The medium scale wind-diesel-compressed air system (MSWDCAS) (Figure 7) combined with diesel engine supercharging, will increase the wind energy penetration rate [34]. Supercharging is a process consisting of a preliminary compression that aims to increase the density of the engine's air intake, in order to increase the specific power (power by swept volume). During periods of strong wind (when wind power penetration rate – WPPR, defined as the quotient between the wind generated power and the charge is greater than 1; $WPPR > 1$), the wind power surplus is used to compress the air via a compressor and store it in a tank. The compressed air is then used to turbocharge the diesel engine with the two-fold advantage of increasing its power and decreasing its fuel consumption. The diesel generator works during periods of low wind speed, i.e., when the wind power is not sufficient to sustain the load. It is important to mention that the TechnoCentreéolien (Gaspé, Canada) has finished, recently, the setting up at its experimental site in Rivière-au-Renard of the only microgrid existing in the world based on the principle of MSWDCAS (Figure 9) [35].

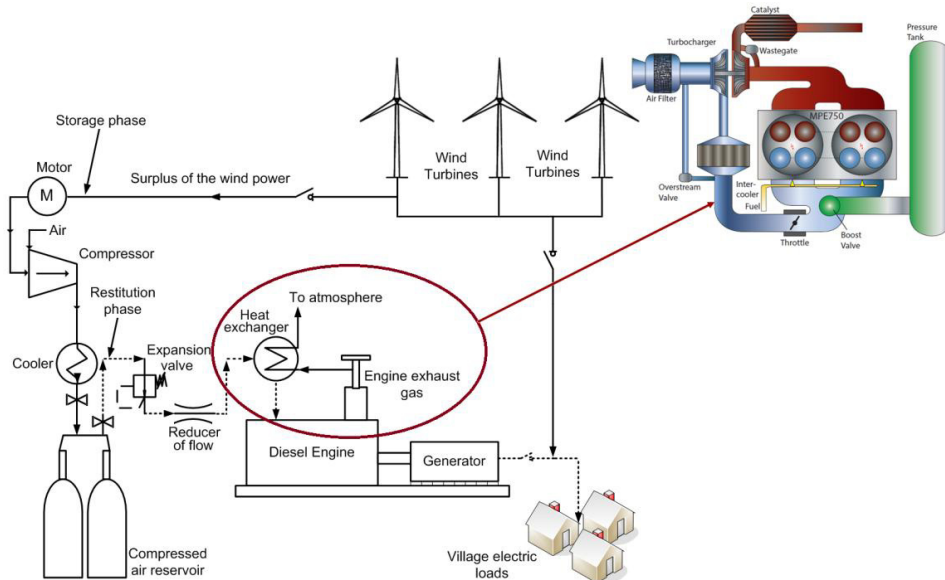


Figure 7: Illustration of the medium scale wind-diesel compressed air system [26]

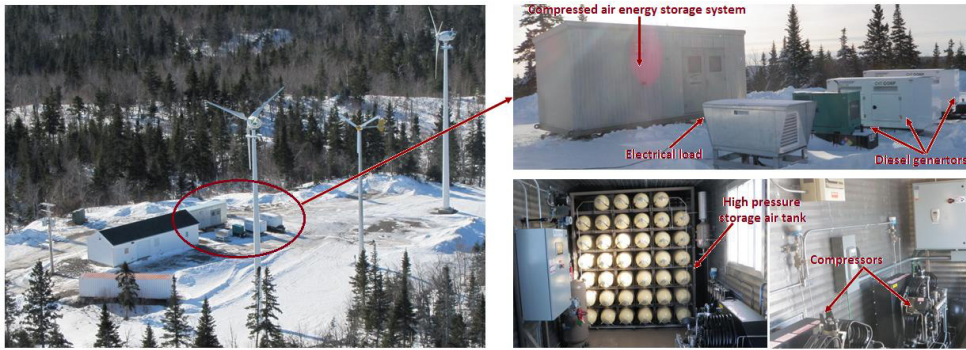


Figure 8: Microgrid of TecnoCentreéolien[35]

2.4.2.2. *Small scale wind-diesel-compressed air system*

The small scale wind-diesel-compressed air system (SSWDCAS) (Figure 9) can be used, for example, to electrify the remote telecom infrastructures that require continuous, stable, and safe energy supply for maximize the deployment, signal strength, and coverage of the cellular phone [36]. The difference between MSWDCAS and the SSWDCAS is the utilization method of the stored compressed air. This latter will be expanded during periods of low wind power ($WPPR < 1$) into a pneumatic generator that supply the load [37], [26], [27]. In this step, the diesel generator is stopped. The genset works during periods of low wind speed and only if the compressed air energy storage capacity is not sufficient to supply the pneumatic generator.

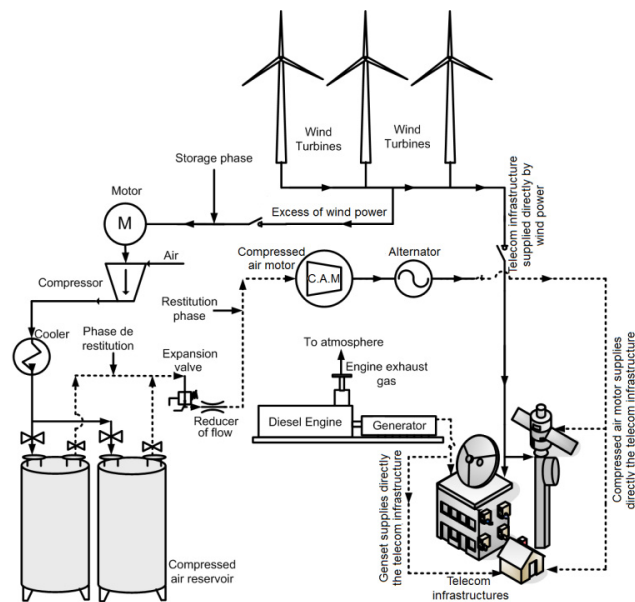


Figure 9: Illustration of the small scale wind-diesel compressed air system [36]

3. Case study applied to the medium scale wind-diesel-compressed air system

To estimate the potential gain of the MSWDCAS on a target site, we recovered the hourly wind speed data and the hourly electrical load of the diesel engine on the site of the village of Tuktoyaktuk in the Northwest Territories of Canada on the Arctic coast. The maximum and average electric loads of this village are respectively 851 kW and 506 kW. Initially, the village's electricity is supplied by 2 diesel generators, each having 544 kW as maximal power. To these generators a wind plant composed of 4 wind turbines of type Enercon, each having a nominal power equal

to 335 kilowatts, a total power equal to 1340 kW was added. We estimated fuel consumption, greenhouse gases (GHG) emissions and maintenance cost of diesel engines for different scenarios: diesel only, wind–diesel hybrid system (WDHS) without CAES and wind–diesel hybrid system with CAES, over a period of 1 year. Figure 10 to Figure 15 illustrate the results.

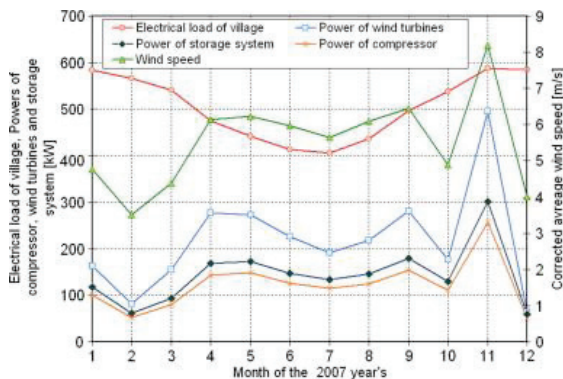


Figure 10: Wind speed and power profiles of the: electrical load, wind turbines, compressor and energy storage system.

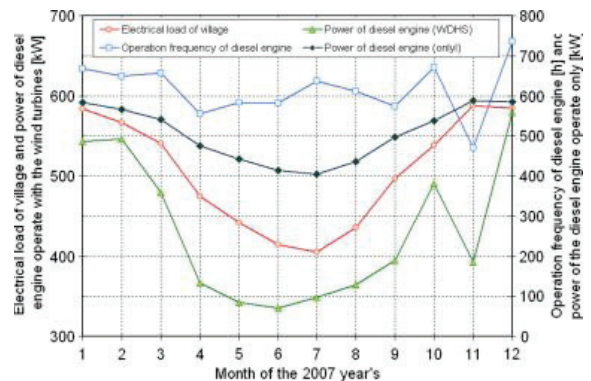


Figure 11: Operation frequency and power curve of diesel engines and profile of the electrical load

Figure 10 and Figure 11 represent the profile of the average wind speed corrected to hub height of wind turbines, the profile of the monthly electric load of the village, the variations of power supplied by wind turbines, the variations of power supplied by diesel generators before and after hybridization with the wind turbines, the operation frequency of diesel engines after hybridization and the profiles of the power directed toward the storage system and that absorbed by the compressor. These figures show that the maximal average consumption of the village occurs during the fall and winter seasons due to the increase of the electric load for the heating. Unfortunately, the highest wind speed is registered during the spring and summer seasons where the average electricity consumption decreases approximately 200 kW in comparison with that of the winter.

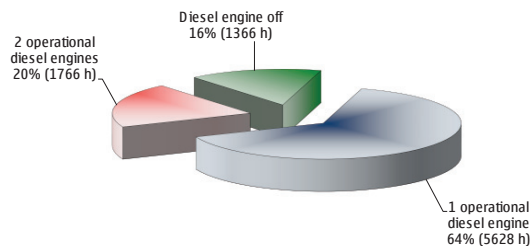


Figure 12: Operation frequency of diesel engines after the hybridization with the wind turbines

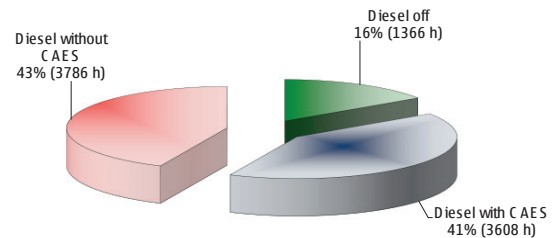


Figure 13: Operation frequency of diesel engines according to their supercharging mode

Figure 12 shows the operation frequency of diesel engines after the hybridization with the wind turbines. The number of functioning hours of diesel engines depends strongly of the availability of the wind power and the level of the electric load of the village. During 2007, the hybridization would have allowed the operation of a single engine during 5628 h (64%), of two engines during 1766 h (20%) and stop both diesel generators approximately 1366 h (16%).

Figure 13 represents the operation frequency of diesel engines according to their supercharging mode (with or without CAES). This figure shows that the hybridization allows the functioning of diesel engines supercharged by

stored compressed air during 3608 h (41%). During 3786 h (43%), the diesel engines are operating without CAES and they are stopped for 1366 h.

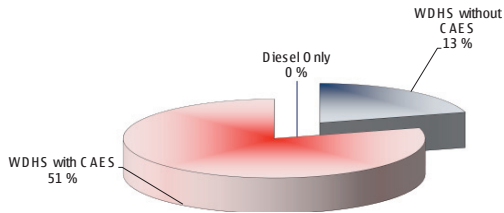


Figure 14: Annual reduction of O&M costs

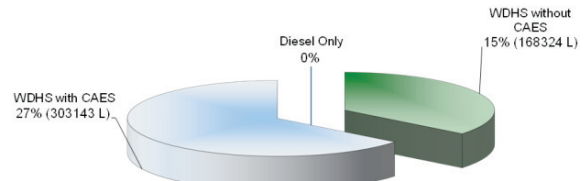


Figure 15: Annual fuel savings

The estimation of the annual reduction of maintenance and operation costs, based on the reduction of operation time of the two diesel engines, is represented in Figure 14. The base line for comparison is the scenario without hybridization, where no savings in the cost of maintenance can be realized. The WDHS without CAES allows 13% reduction while with CAES, this rate increases to 51%. It is important to mention that the supercharged diesel engine by compressed air stored allows operating with a single diesel engine, whatever the load of the village. On the other hand, a permutation between the two supercharged engines will be necessary to avoid the blocking of some mechanical moving pieces of the engine. Figure 15 illustrates the annual fuel savings. The hybridization between wind energy and diesel engines without CAES reduces by 168,324 L the annual fuel consumption (15%) while with CAES, this reduction increases to 27% (303,143 L). This quantity (27%) is equivalent to 848.8 tons of CO₂ or the annual emission of 167 vehicles and light trucks traveling 15,000 km/ year.

4. Case study applied to the small scale wind-diesel-compressed air system

To estimate the potential gain of the SSWDCAS on a target site, we recovered the hourly wind speed data (for one month, April 2005) on the site of the telecom station of Bell-Canada situated in Kuujjuarapik (North of Quebec) at 1130 kilometers from Montreal (Figure 16). The electrical load of the station is considered constant, about 5kW, including the secondary load of heating. The diesel generator guarantees the supply's continuity of the station by providing exactly the power level consumed by the load. The case study was conducted using two types of wind turbines: the first is a Bergey[38] (10kW, already installed on site) and the second is a PGE (currently named Endurance, 35kW) [39] that we propose to be able to increase the penetration of wind energy and use the excess of this energy to produce the compressed air. Figure 17 to Figure 20 illustrate the obtained results.



Figure 16: Telecom station of Bell-Canada at Kuujjuarapik[40]

It is interesting to observe, in Figure 17 and Figure 18, the advantages of hybridization (Diesel + PGE + CAM) that appears in the short duration of the diesel operation time (DOT). Indeed, it can stop completely the diesel

generator for 33 hours during two days of operation (saving of 69% of the DOT) compared to 13 hours of shutdown of the diesel (27% of DOT is avoided) obtained through the system (Diesel + PGE) and 1 hour (saving of 2% of the DOT) during which the diesel will be stopped thanks to the hybridization between it and Bergey wind turbine [26], [27].

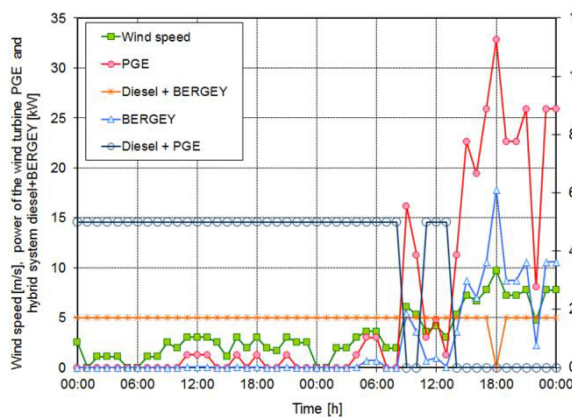


Figure 17: Operating modes of the studied systems along period from 4 to 5 April 2005 [36], [37]

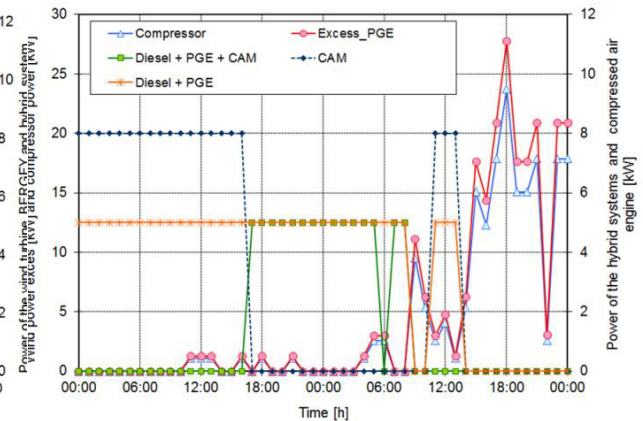


Figure 18: Operating modes of the studied systems along period from 4 to 5 April 2005 [36], [37]

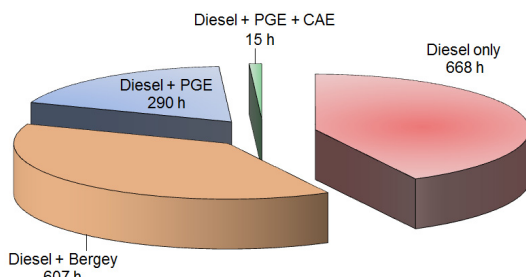


Figure 19: Operating time of diesel generator according to the exploitation scenarios [36], [37]

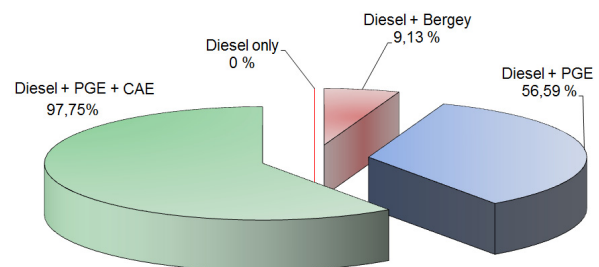


Figure 20: Fuel saving according to the exploitation scenarios [36], [37]

Figure 19 represents the operating time of DG according to the functioning scenario of the system (diesel only, Bergey + diesel, PGE + diesel or PGE + diesel + CAM). Figure 19 shows that hybridization between the Bergey wind turbine and diesel does not allow a remarkable decrease in the operation frequency of the diesel generator (DG) that runs about 91% of operating time in April 2005 (607 h). But by combining the DG to a PGE wind turbine, the DG will work almost 43% (290 h) of time during the month of April and 15 h (2%) if it works in hybridization with the CAM and a PGE wind turbine [26].

Figure 20 represents the fuel saving according to the functioning scenario of the system (diesel only, Bergey + diesel, PGE + diesel or PGE + diesel + CAM), Figure 20 shows that WDHS avoids approximately 139 liters of fuel (9% saving in fuel consumption) if the diesel is associated with a Bergey wind turbine [27]. However, this rate increases to 57% (863 liters), if the hybridization of the diesel generator is done with the PGE wind turbine. On other hand, the hybridization between diesel generator, compressed air generator and PGE wind turbine can increase this fuel saving very significantly where the amount of fuel avoided is approximately 1491 liters (98%). The fuel saved thanks to SSWDCAS, allows to reduce the greenhouse gases (GHG) emission approximately 4 tons, which is equivalent to the GHG amount emitted by automobiles and light trucks traveling 15,000 km per year [25].

5. Conclusion

This study provides an overview of the state-of-the-art of CAES technology development. CAES operates in the way of storing energy in the form of high pressure compressed air during the periods of low electric energy demand or high penetration rate of renewables energies (wind, solar, ...) and then releasing the stored compressed air energy to generate electricity to meet high demand during the peak time periods. CAES can be built to have the scales from small to large and the storage durations from short to long with moderate response time and good part-load performance. Any one CAES installation refers to the establishment of a system with integration of different interacting components, devices and processes, such as compressors, turbines/expanders/air motors and electrical machines. CAES is often hybrid or combining with alternative energy storage technologies to achieve the required energy capacity, energy density, response time or efficiency. For instance, the combination of CAES with thermal energy storage will reuse the heat generated from compression process which will improve the round-trip efficiency.

This study have introduced the working principles of CAES used in several applications (small, medium or large-scale) especially in power systems integrating wind turbines, current technology development, typical technical characteristics, existing facilities and application. A case study which demonstrates the use of compressed air in microgrid to supply the remote areas was, also, presented.

The case studies conducted on the medium and small scale wind-diesel compressed air (MSWDCAS & SSWDCAS) represent an innovative concepts designed to overcome most of the technical, economic and social barriers that face the deployment of wind energy in isolated sites. Indeed, implementation costs are minimized and reliability is increased by using the existing diesel generators. Thus, the results, theoretical and experimental, obtained have demonstrated the great potential of wind-diesel-compressed air energy storage system for both types of applications: small and medium scale. The application of these systems on real case studies has demonstrated that the fuel economy obtained with MSWDCAS and SSWDCAS is about 27% and 98% respectively.

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