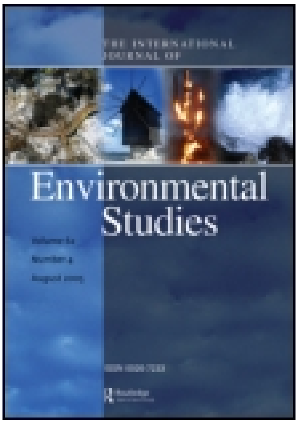

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Geological compressed air energy storage as an enabling technology for renewable energy in Ontario, Canada

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As renewable resources are increasingly used to provide power to the world's demand centres, dealing with the intermittent nature of these resources and their affect on the power grid is becoming a significant issue. Compressed air energy storage (CAES) is one technology that is proposed to increase flexibility when integrating renewable energy sources such as wind, solar and tidal generation with the power grid. By creating a storage medium where the energy produced from these sources can be stored and dispatched to the grid as required, a higher penetration of renewable energy generation can be achieved.

Keywords: Compressed air; Energy storage; Energy arbitrage

1. A survey of compressed air energy storage

1.1. Context and objectives

In 2008, the United States generated 4.119 billion kWh of electricity, 3.1% of which was generated through renewable sources such as wind, solar and biomass (excluding conventional hydroelectric) [1]. Clearly, conservation of energy resources and reduction of carbon emissions are both key in planning future generation assets and engaging other electricity infrastructure issues. Compressed air energy storage (CAES) is a technology that can be used to fulfil two major niches in the electricity market. The first is an arbitrage mode where energy is stored in order to leverage low off-peak energy prices against higher peak prices. The second proposed mode of operation is in conjunction with renewable energy sources like wind farms. These two modes represent significant uses of energy storage. Further detail can be found in the Sandia Report (2010) [2]. The combination of CAES and renewable energy will be discussed more thoroughly here. CAES facilities combined with renewable energy sources can solve some problems associated with maximising these

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environmentally friendly forms of electricity generation. For example, wind turbines often produce power at off-peak times. This may require that their operation be curtailed because although the electricity is available, there is insufficient transfer capacity to deliver the electricity to demand centre. This curtailment is not desirable for wind farm owners who then lose that potential revenue. A CAES facility co-located with a wind farm could alleviate this by allowing the excess power to be stored and released to the grid when it is required. In this way, CAES can serve to increase wind power penetration into the North American electricity market by making it 'dispatchable'.

The aim of this study is to identify which factors will affect the site selection and planning of CAES facilities as well as to enumerate the risk factors associated with these facilities. This is considered a stepping stone to a feasibility study where the selected factors will be studied in-depth and additional influences will be identified and characterised. The authors recognise that some of the information in this paper may seem to be restricted to Ontario, but the research can be helpful in the assessment of the viability of CAES elsewhere in North America.

1.2. What is CAES?

Compressed air energy storage (CAES) is a technology; which compresses air to store it for use in power generation. A traditional CAES facility as depicted in figure 1 consists of five major components: a compressor train, a motor/generator, a storage cavern/reservoir, a combustion chamber and an expander train. A more detailed survey is found in Gardner and Haynes (2007) [3].

A CAES facility consumes energy to store compressed air underground. The power used can be obtained from renewable sources such as wind, and solar, or from traditional sources such as nuclear. When the facility is operated in generation mode, the stored air is expanded through the combustor and mixed with a fuel such as natural gas (number 2 fuel oil has also been used). The mixture is burned to add heat energy to the stream. The hot gas stream then flows through the turbine, which drives the motor/generator as a generator and the facility sells electricity back to the grid at a higher price. In more advanced designs, the waste heat from the combustion process is used to pre-heat the expanding air

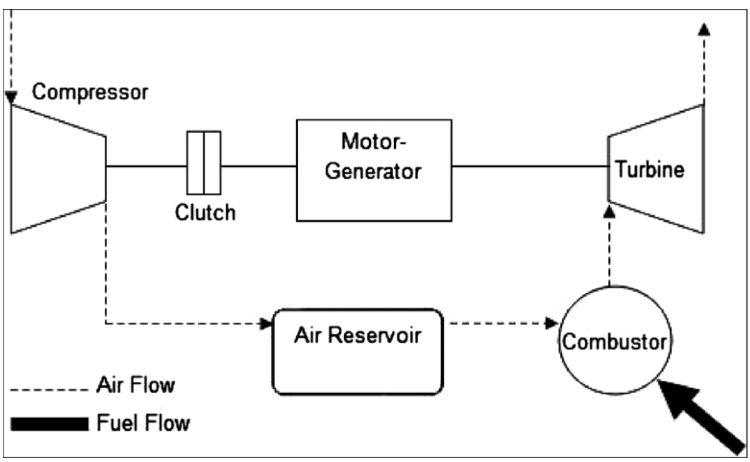

Figure 1. Layout of a traditional CAES facility.

before it enters the combustor, thus reducing the fuel usage and increasing overall efficiency. By reducing fuel usage during the electricity generation process, CAES also helps to reduce emission levels.

The storage of compressed air underground as part of a CAES facility is principally justified on the basis of minimising use of the land surface, avoiding the maintenance of easily corroded, limited size surface tanks, and reducing storage costs. The main options for a CAES reservoir in places such as southwestern Ontario are depleted oil and gas reservoirs, reservoir configurations of strata without hydrocarbons, and artificial caverns, formed through the controlled solution mining of salt deposits.

When co-located with a renewable energy source such as a wind farm, a CAES facility can function as a buffer to reduce or eliminate curtailment and reduce the use of fossil fuels for generation. Power plants using coal and natural gas as their fuels are currently used to respond to short-term spikes in demand. Because of the ability to change quickly the output of these plants, and the fact that they are typically kept running at idle speeds to reduce response time, they are termed 'spinning reserve' plants. The design similarity between CAES and fossil fuel power plants would allow CAES to function also as spinning reserve, and, if coupled with a renewable energy source, would create a 'renewable spinning reserve'. By attaching a CAES facility to the grid, the ability to store energy can be used to assist in load balancing when demand is changing by either storing or generating energy as demand requires.

1.3. CAES and renewable energy

In international markets such as Denmark [4] that have high levels of renewable energy generation, CAES has been identified as a possible solution to the variability of renewable energy sources. By enabling these higher levels of wind penetration, CAES can enable electricity producers to lower their fuel consumption and emissions profiles. Because of the rapidly increasing amount of wind energy generation in Ontario, and the comparable amount of nearby hydroelectric energy sources, it is used as a case study in this section.

1.3.1. Variability of wind in southwestern Ontario

Power demand and wind speeds (and therefore available power from wind energy) vary not only hourly, but seasonally as well. Figure 2 shows a 72-hour moving average of both wind speed and Ontario power demand for the period from 1 January 2010 to 31 December 2010. The use of a moving average, where each data point is averaged over the previous 72 hours of data, smooths the data to show more clearly the associated seasonal trends.

Inspection of figure 2 shows increases in Ontario's power demand during the winter and summer months. It can be observed that situations may arise where the ability to store power generated by wind turbines over long periods of time would be desirable. The daily trend shown in figure 3 depicts a situation where CAES could be used to store otherwise wasted power and supply it to the grid during peak demand. Figure 3 presents the average hourly wind speeds and power demand in southwestern Ontario for August 2010. Weather data were chosen from the Sarnia, Ontario station and Ontario power demand data were collected from the IESO [5]. It can be inferred that although these figures represent only a small amount of the data available, situations which can make available storage advantageous do occur on a regular basis when renewable energy resources are included in the mix of generation options.

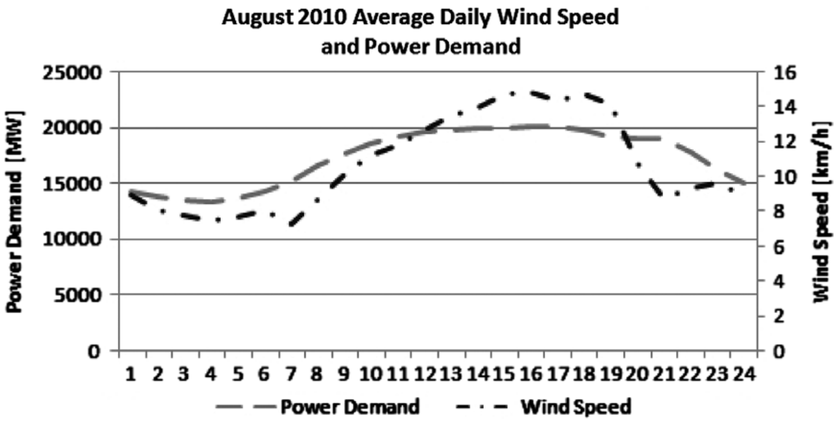

Figure 2. 2010 yearly wind speed and power demand.

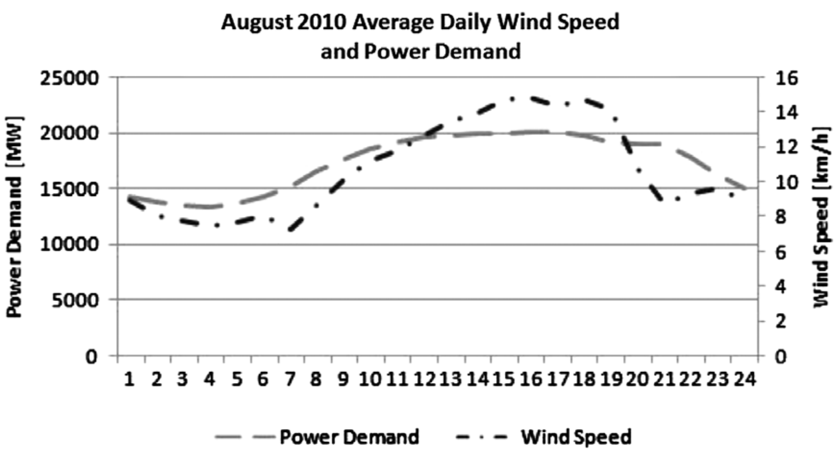

Figure 3. Power demand and wind speed, August 2010.

1.3.2. CAES as a buffer for renewable energy

Figures 2 and 3 show the potential for an energy storage facility to act as a buffer between renewable energy sources and the power grid in Ontario. By using a CAES facility in this way, renewable sources such as wind and solar could be left 'always-on' as opposed to curtailing them when transmission capacity is not available. The capacity to store this power when it is available affords the grid an on-demand source of electricity while reducing fossil fuel usage and taking advantage of renewable resources.

It is also possible to foresee a configuration in which the CAES facility could be bypassed when conditions allowed for the renewable energy source to provide power to the grid directly. Further study of methods and configurations is required, and is continuing to quantify this relationship better. This has been undertaken also by others [6–8]. By increasing renewable generation penetration, CAES can reduce reliance on fossil fuels and decrease the reliance of our electricity generation system on those energy sources.

1.4. Existing CAES facilities

Two CAES facilities are currently in operation worldwide. Both use similar design and operating principles, as well as storage media. Several other proposed CAES projects are in various stages of proposal and completion. The operation of existing CAES facilities provides prior work from which a second generation CAES facility could be developed in Ontario.

1.4.1. CAES at Huntorf, Germany

This 290 MW CAES facility was built in 1978 and is used to provide spinning reserve power to the German grid [9]. It is co-located with the Unterweser nuclear power plant and provides power to the grid during peak demand. It is designed to provide full rated power for 2 hours. This time limitation is a function of storage capacity. The Huntorf facility uses two solution-mined salt domes with a total volume of approximately 300,150 m^3 (10.6 million ft^3). This facility is designed to go to idle power in 2.5 minutes, followed by a 90 MW/minute increase to full rated capacity. Allen *et al.* have provided information on the geological stability and site selection of this facility [10]. Crotogino *et al.* have provided further information on the history of this facility [11].

1.4.2. CAES at McIntosh, Alabama, USA

Like the Huntorf facility, the McIntosh facility uses a solution-mined salt cavern for energy storage. Unlike Huntorf, it is rated to provide 110 MW and has a total capacity of 2600 MWh before requiring the cavern to be recharged. During testing in August 1992, the plant ran in generation mode continuously for 26 hours. The total volume of the storage cavern at this facility is approximately 538,000 m^3 (19 million ft^3) [9].

This facility is capable of being brought from start to full load in less than 15 minutes. Shidahara *et al.* have given more information on the geology of this facility [12]. Pollak has given further information on the history of this facility [13].

1.4.3. Proposed and planned CAES facilities

There are currently several CAES facilities planned in North America. The first is being sited in Norton, Ohio. Discussions are underway for additional facilities in Texas, New York, and California respectively although planning for these facilities is at the early stages [9].

1.5. The Ontario electricity market and development of renewable energy resources

Between 2006 and 2009, more than 1080 MW of wind generation capacity were installed in Ontario. With another 50 MW scheduled to come online in Quarter 4 of 2010 and 860 MW scheduled between Quarter 1 of 2011 and Quarter 2 of 2012 [5]. Over 2009 and 2010 the average hourly power demand in Ontario was 16.1 GW. While Ontario's installed wind power capacity is relatively high, solar photovoltaic installations are only slowly being introduced.

The Ontario Power Authority intends to increase Ontario's renewable energy generation capacity (wind, solar and biomass) to 13% by 2018, from 3% today. The Authority's plan requires a large increase in renewable energy generation, but they also plan to cut total demand by 28 TWh by 2030 [14].

With the large increase in renewable energy's contribution to electricity generation in Ontario's electricity market, the variability of these energy sources needs to be confronted. While the contribution from solar photovoltaics is relatively predictable based on prevailing weather conditions, the output of wind farms is highly variable. Some element of energy storage will be required by the electricity system operators in order to act as a buffer [15], allowing this power to be dispatched and reducing Ontario's reliance on simple-cycle and combined-cycle gas turbines for peak power generation.

2. Geological and geographical considerations for CAES in south-western Ontario

Sedimentary strata with CAES potential attain a maximum thickness on the order of 1400 m in the Sarnia area and under central Lake Erie. They rest on a basement of crystalline Precambrian rocks and thin northeastwards to pinch out along the southern perimeter of the Precambrian Shield. The sedimentary rocks of the area range in age from Upper Cambrian to Upper Devonian [16,17]. In general, they thicken from the central part of southwestern Ontario west and northwestward toward the Michigan basin and also east- and southeastward in the direction of the Appalachian (Allegheny) basin. Strata with reservoir potential – and closely related CAES potential – occur throughout the sedimentary sequence. The Silurian part of the succession contains the carbonate reefs of the Guelph Formation and the overlying salt-bearing strata of the Salina Formation [18–20], both of which have CAES potential.

2.1. Bedded salt deposits

Solution-mined caverns in salt have proven successful for storage in existing CAES facilities like Huntorf and McIntosh [9,21,22]. This indicates particular promise for parts of southwestern Ontario, where solution-mining operations already exist. Bedded salt deposits, referable to the Salina Formation, occur over large areas of southwestern Ontario. The main salt-bearing strata occur in the Salina A-1, A-2, B, D, E and F units, in which rock salt is interbedded with dolomite, anhydrite and shale. These salt units are found along the western margin of the Michigan basin, from Amherstburg northward to Kincardine.

At both existing CAES facilities, the salt caverns were mined for the purpose of storing air for CAES. Although this is feasible in Ontario as well, the existence of previously-mined salt caverns provides an economically more attractive option. Fresh solution mining operations give facility designers the opportunity to control the size and aspect ratio of the caverns; and solution mining of new caverns has the potential to add significant cost and time to construction. There are also salt-mining operations in the Windsor area and at several locations between Courtright and Kincardine. These include both producing and abandoned brining operations, as well as the producing mines at Windsor and Goderich.

2.2. Reservoir storage

Commercial quantities of hydrocarbons have been discovered throughout the sedimentary sequence of southwestern Ontario. The Cambrian strata, the Gull River, Coboconk, Kirkfield, Cobourg and Sherman Fall strata (Ordovician), the Whirlpool, Grimsby, Thorold, Irondequoit, Guelph, Salina A-1 and Salina A-2 strata (Silurian) and the Dundee

Formation (Devonian) yield natural gas. The Cambrian, Sherman Fall, Whirlpool, Grimsby, Guelph, Salina A1, Lucas and Dundee strata contain commercial accumulations of crude oil. All of these reservoir units offer potential storage media for CAES facilities.

Configurations of strata, prospective for hydrocarbons and also potentially suitable for CAES applications, occur 1) along the western margin of the Appalachian basin, 2) on the eastern edge of the Michigan basin, and 3) on the Findlay arch. The pinnacle and patch reefs of the Silurian Guelph Formation hold particular promise for CAES, both as depleted hydrocarbon reservoirs and as trapping mechanisms, devoid of oil and gas. The Salina A-1 and A-2 carbonate traps are located directly above Guelph reefs, which in many cases occur along the crests of tilted, fault-bounded blocks. Secondary recovery is widely employed in oil and gas exploitation in southwestern Ontario. This process uses water flooding with a line drive or five-spot and nine-spot patterns of wells. Accordingly, reservoir performance has been extensively documented for many pools. Nevertheless, the penetration of producing reservoirs by recovery and injection wells may limit their potential for adaptation to CAES use. It is worth noting that some of the Devonian reservoirs were damaged by poor production practices [12].

The formerly planned Iowa Stored Energy Park (ISEP) was slated to use an aquifer for storage of compressed air. There are many uncertainties with the use of this geology. It is possible that residual water in an aquifer could prevent airflow and restrict the number of paths that air can take when entering and exiting the reservoir. As the air is cycled through the cavern, the available paths could change as water migrates throughout the porous structure. The effects of air cycling on aquifer structure require further study before usage of specific aquifers is determined to be suitable for CAES in a particular location [23].

2.3. Guelph reefs

The carbonate mounds of the Guelph Formation occur as pinnacle reefs, with relief of up to 165 m, in a band 16–32 km wide, to the south of Lake Huron, and as patch (incipient) reefs, with relief generally in the range of 10–30 m and located to the south and east of the others. The pinnacle reefs are elongated in plan, with average lateral dimensions of 1500 m long by 650 m wide. The enveloping rocks are the evaporite-bearing strata of the lower part of the Salina Formation. The Guelph patch and pinnacle reefs and overlying Salina A-1 and A-2 carbonate traps are the most productive in the area. Depleted hydrocarbon reservoirs in reef carbonates of the Guelph Formation have been converted for the underground storage of natural gas in Lambton County. Because Guelph reefs are potential hydrocarbon reservoirs, the hydrocarbon content must be known before adding compressed air to the reservoir.

2.4. Mechanics of porous rock

While Guelph reefs comprise the majority of viable porous-rock type formations available in southwestern Ontario, additional work has been done to characterise the air flow in these and other types of porous rock. Azin [24], Allen [25], and Kushnier [23] recognised the importance of these reservoir types. Their characterisations provide a basis for further work on the types of reservoirs that may be available in Ontario. These types of reservoirs, though more abundant, may provide unique challenges to designers of next-generation CAES facilities which were not faced by those developing facilities using open-cavern storage media.

2.5. Locations of viable wind resources in southwestern Ontario

Data on average wind speeds were acquired from the Ontario Ministry of Natural Resources (for example, figure 4). These data show average wind speeds at a height of 80 m above ground level (AGL). Data are available at 20 m intervals. Additionally, the location of existing wind and solar resources is also shown. When co-location of CAES and wind farms is discussed, the location of viable winds in relation to appropriate geology for CAES could be a critical factor for selecting a location for the CAES facility. Therefore it is necessary that such data are readily available for a first approximation of a CAES/wind site. In areas with already high levels of wind energy penetration, CAES could facilitate further development of wind resources [3].

2.6. Economic considerations

In petroleum exploration, sometimes geology that would normally be expected to contain trapped hydrocarbons for some reason does not. Often these formations consist of porous rock; which has a history of gas storage. In terms of CAES, this geology would be an economic success because it would be suitable for storage of compressed air.

In addition to this geology, the cost of excavating caverns or solution-mining salt needs to be considered in any economic model. This cost is non-trivial especially for the very large reservoirs required to support plants for base load provision.

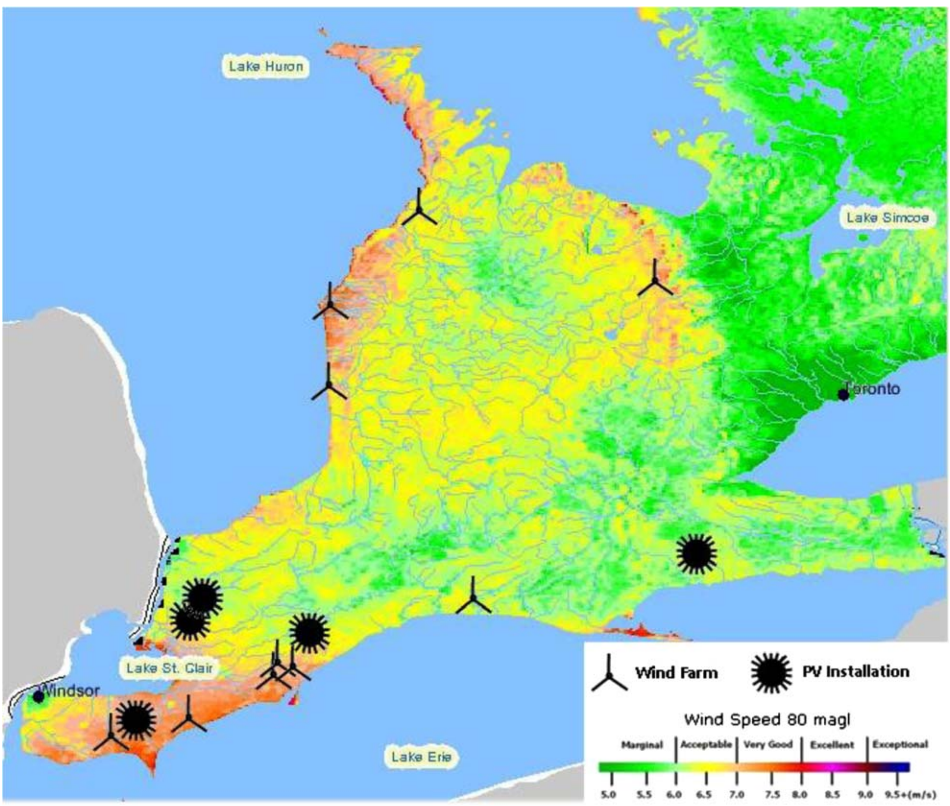

Figure 4. Wind speed at 80 m AGL and renewable energy resources [26].

As discussed in the previous sections on the geology and geography of southwestern Ontario, viable wind resources that are already being exploited coincide with appropriate geology for CAES across this area of the province. The Sarnia area appears to be particularly viable for development of a CAES facility due to the existing power generation and petroleum recovery infrastructure. The existence of porous rock-type geology which may have the required wellhead infrastructure already in place could significantly decrease the cost of developing underground space for a CAES facility.

Further, work completed on the economics of similar storage systems for natural gas [27] can provide an economic basis with which electricity system operators can make correct decisions when it comes to operating a CAES facility. The work of Thompson [28] and Zhao [29] on economic control of power plants in market economies could strongly influence the operator of a CAES facility.

3. Conclusions and recommendations

This brief survey of the state of CAES technology and development of CAES facilities shows the potential for further development in the Ontario electricity generation market. As an enabling technology for higher penetration of renewable resources, CAES can provide the necessary storage medium to supplant the variability and lack of 'dispatchability' in wind generation. As a standalone technology, it is evident how a CAES facility could operate for profit and assist with grid balancing by conducting energy arbitrage.

Either way, CAES technology can reduce overall fuel usage and assist electricity generators in better using existing resources while reducing emissions at the same time. Higher levels of renewable energy generation enabled by CAES will strengthen this effort.

Through careful analysis of existing CAES facilities, an optimised solution for the Ontario electricity market could be conceived. The results of this research create a basis for a feasibility study of CAES in Ontario. By understanding the underlying geological and geographical constraints, a site selection study could proceed as the first phase, followed by an engineering and economic evaluation, and a subsequent optimisation of the facility. The completion of this prefeasibility examination provides the impetus to consider further the potential of CAES to serve as an enabling technology to assist the province of Ontario and other interested parties in meeting their renewable energy generation goals in the near term.

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