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Study and Evaluation of Liquid Air Energy Storage Technology For a Clean and Secure Energy Future

Challenges and opportunities for Alberta wind energy industry

Hadi H. Alyami*[1], Ryan Williams*[2]
[1] *School of Electrical and Computer Engineering*
[2] *School of Business*
* *Faculty of Graduate Studies and Research*
University of Alberta, Edmonton, Canada

Abstract: *Global energy demand is steadily increasing each year. Many jurisdictions are seeking to incorporate sustainable and renewable energy sources to help meeting the demand and doing so in a responsible method to the environment and the next generation. In a wide-context, renewable energy sources are promising, yet cannot be controlled in such a way that is responsive to energy demand fluctuation. Liquid Air Energy Storage (LAES) technology seeks to bridge the gap that exists between energy supply and demand in an effort to mitigate the current demand deficiency. The volume ratio of air to liquid air is nearly 700:1. Liquid air is a dense energy carrier that is by converting renewable energy at off-peak periods into liquid air the energy can be stored until a peak-demand period when energy producers are maximising output to meet the demand. The energy is then retrieved from the liquid air through rapid expansion as it re-gasifies through a gas turbine and converted into electricity. A commercial scale pilot plant in Slough, UK illustrates the application of this technology empirically. The application of this technology in Canada might have challenges as public policy respective jurisdictions play a role. A case of point of applications where LAES can be integrated is the renewable energy market; particularly the wind power in Alberta. This paper's analysis embraces wind power industry in Alberta from the perspective of both the electric system operator and the power generation plant. As such, it serves as an alleviating proposal of the current wind energy issues in Alberta – including the uncertainty of forecasting system. The analysis assumed energy storage technologies as a viable stand-alone mitigation with no consideration of the current technological and operational advancements in power systems such HVDC grids, distributed generation concepts and among others.*

Key Words: LAES technology, Wind power in Alberta, Power shifting, LAES arbitrage opportunities, Energy demand.

I. Introduction

Power energy is a key element of the modern life that is usually taken for granted in many developed nations. This paper's motivation is to accelerate the flexibility of the current base-load facilities toward a future of power energy where production can more easily meet demand peaks without the use of peak-load facilities. Therefore, the major motivation for LAES technology deployment is enabling more efficient utilisation of existing base-load facilities via load-levelling demand response technique and renewable-based energies integration. LAES system is among the best energy storage technologies and can be readily deployed anywhere in which air is available [1], [2].

At present, power grids operate in a momentary-time strategy that matches instantaneous supply with instantaneous demand. This strategy serves the power grid well; however, the aspiration to eliminate GHG emissions through the integration of renewable energies introduces critical challenges that affect the momentary-time strategy [3], [4]. Renewable energies, also referred to as variable generation, are variable and intermittent in nature for which their power outputs fluctuate and are difficult to predict. As a result, in the last two decades, the need to deploy energy storage systems as a vital component of the future power grid that incorporates more renewable energies has been rapidly growing [5].

1. Background

I. Demand for Energy Storage Systems

Energy storage systems have been adapted to numerous small-scale, low-powered apparatuses and to large-scale, high-powered systems. Although they are mature in low-powered (less than a few kW) applications, technical and economic obstacles still exist for high-powered applications (more than $1MW$) [6]. The evolution from variable generations to stochastic generation, the resurgence of micro-grids as essential component in distributed grid construction, the gradually strained infrastructure of transmission systems as new lines lag behind power demand, and the necessity for growth in the security and reliability of power supply are all emerging grid technological advancements whose operations will stimulate the need for energy storage systems [7], [8]. Fig. (1) illustrates the benefits of energy storage systems to the emerging technologies in the electric power grid industry.

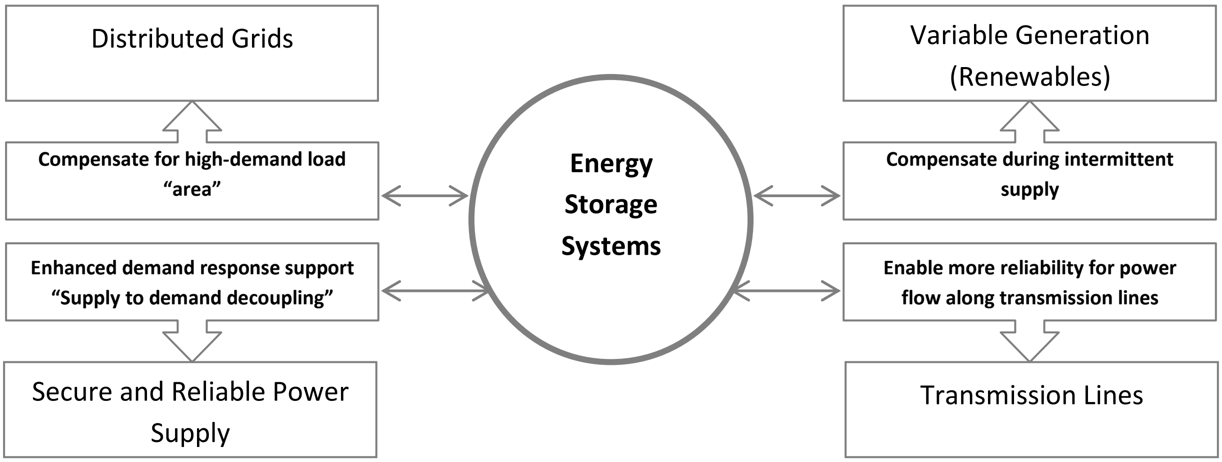


Figure 1: Factors for grid energy storage systems

In stationary applications, energy storage systems play a major role in the overall reliability of the power grid system [9]. The power supply-to-demand needs must be precisely balanced so that as the natural fluctuation of power demand increases or decreases, the power supply compensates accordingly. However, it is reported in [10] that power demand is fairly stable to some extent and only varies considerably during a short period relative to the annually-operated power grids. This means power grids must be designed to satisfy peak demands that only last for short durations [5], [11]. Thus the power grid's capacity is utilised optimally. Instead, the excess power can be stored during off-peak demands and released back when demand returns. Therefore, energy storage systems can serve as a penance for which the power supply can be decoupled from power demand, thereby ensuring higher security and reliability. Power supply-to-demand decoupling can also significantly reduce power costs, as dissipated power is lower, allowing more renewable energy deployment, which is in fact the main driving force behind the development of power storage systems.

II. Energy Storage Technologies in Electricity Network

Energy storage technologies are not recent advances but comprised the plethora of 18th century discoveries, for instance, the gasoline-filled tank in vehicles and airplanes [14]. In pumped-hydro storage (PHS), an example of a stationary application that put into use since the 1990s, water is pumped overnight into a high reservoir and released during the day when demand peaks [9]. However, energy storage technologies have only gained serious attention over the last decade when the electricity industry became more complex; as a result of the integration of renewable energies, the spanning of long distances by transmission and distribution systems and the steady increase in power demand. Therefore, due to the prevalent introduction of electric power, energy storage systems became a major factor in economic development. A case in point is that electricity must be consumed as it is being produced, otherwise, it will be dissipated as heat if not promptly stored [15]. In general, electric power can be effectively converted into potential, kinetic or chemical energy forms. Each form has different requirements and is suitable for certain applications and systems. The potential of electric energy storage is complicated by the fact that the wide range of storage technologies are either already commercialised, in development or under examination, from which the selection among the various technologies will be critical. Energy storage systems can be classified based on their stored energy form and their tangible functions [4], [7]. In terms of tangible functions, these technologies can be classified based on their power ratings and storage durations as shown in Fig. (2).

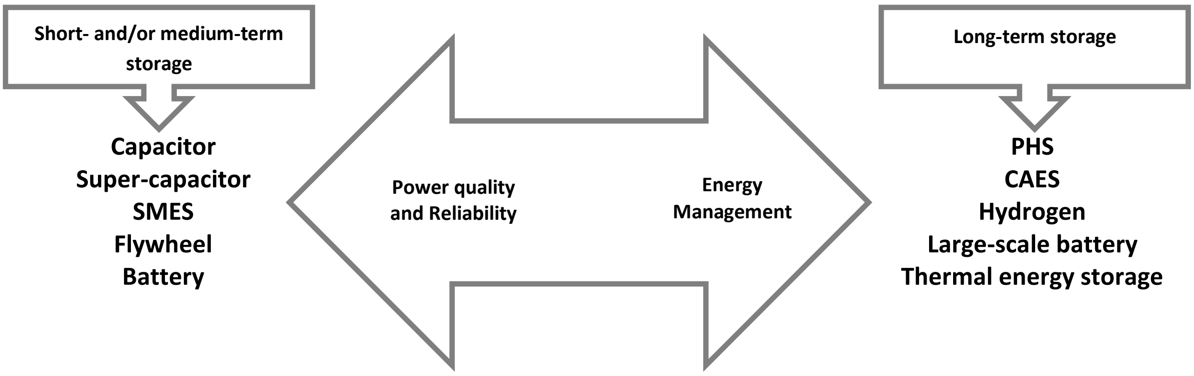


Figure 2: Evaluation of energy storage technologies

In terms of power quality and reliability, energy storage systems should be cap able of responding to power demands on a momentary basis without the need of continuous discharge at any given time, whereas in terms of energy management, energy storage systems should be capable of shifting bulk amount of power over long periods of time (hours and days) [16]. Technologies within the energy management category can be deployed as either Demand Side Management (DSM) for electric and thermal loads, or Supply Side Management (SSM) for reliable and economic power supplies [16].

Pumped-hydro system (PHS), compressed air system, and sodium sulphur and lead acid batteries are currently the most widely considered storage technologies [3]. They are mature and reliable technologies; nevertheless, they still offer some challenges, including geographical requirements and risks for PHS and the underground compressed air system as well as the usual high cost and low power density of batteries. Liquid air energy storage (LAES) is an emerging power storing technology that could play a major role in storage systems development.

III. Liquid Air Energy Storage Technology

The philosophy that air could be turned into an energy vector, or “energy carrier”, dates back to the 1900s, when the US company, Tripler, attempted to establish a simple liquid air-driven vehicle that competed with the electric and steam vehicles [2]. However, the emergence of the internal-combustion engine, along with the required inefficient and bulky external heat exchanger for the liquid air-driven vehicle has decelerated liquid air technology development [18]. This was not until the beckoning of the 20th century when serious interest in liquid air technology or cryogenic energy in general was rekindled. This technology thus expanded to include stationary systems, besides automobile applications, where it has found great acceptance [19].

In 2001, P. Dearman established and patented the Dearman-engine, whose operation is based upon vaporised liquid air inside an engine cylinder utilising heat obtained through a thermal fluid mixture of antifreeze and water [20]. This led to eliminating the necessity for the external inefficient, bulky heat exchangers of traditional liquid air engines. In 2006, the Highview Power Storage Plant, the first plant incorporating liquid air “nitrogen” as an energy storage carrier in the world, developed Dearman’s insight into a grid-scale ($25MW$) energy storage system [10]. The remarkable success of the Highview Power Storage Plant has brought great interest in the technology particularly for large-scale storage applications.

Air can be liquefied when its temperature is reduced to -195℃ using standard industrial mechanisms – compressors, heat exchangers and turbines [10]. The air liquefaction process is illustrated in Fig. (3).

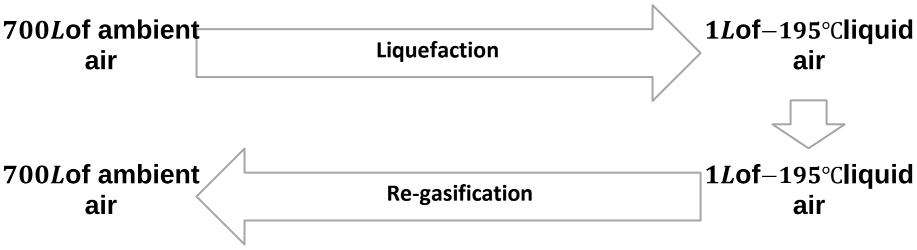


Figure 3: Air liquefaction process

It is clear that through liquefaction,$700L$ of ambient air can yield $1L$ of low-temperature liquid air, which can therefore be stored in an unpressurised insulated tank. When heat is re-established during re-gasificationto the stored liquid air it expands 700 times in volume. This expansion is capable of spinning a turbine to generate electric power via an electric generator. Air mainly consists of nitrogen (78%), and oxygen (21%), among other gases, which can be separated, as they liquefy at different temperatures (nitrogen at -195°C and oxygen at -182°C). An air separation unit is used for this purpose [21]. Air is firstly cleaned from contaminants, such as CO_2, using dust filters, and compressed to 6 bars. The compressed air is then refrigerated to 16°C. Water and CO_2, which are produced at this stage, need to be removed in a process called adsorption, otherwise they would freeze and block the pipes [21]. The partially cooled air is then extremely cooled down to liquefaction temperatures and then passed through a heat exchanger. The super cold air (below -150°C) is now separated in a manner in which the liquid settles to the bottom and gas rises to the top. When the temperature decreases to -182°C oxygen liquefies, as does nitrogen when the temperature decreases to -195°C. Accordingly, they can be stored in an unpressurised insulated tank. The amount of liquefied nitrogen is almost four-fold greater than liquefied oxygen; this attribute provides more credibility to the liquefied nitrogen. Therefore, a new method, called “Frond-end”, is developed in which air can be turned directly into liquefied nitrogen. Liquefaction methods, which have developed rapidly, can be categorised as Cascade Cycle, Mixed Refrigerant Cycle (MRC) and Expander Cycle. Cascade cycle and MRC incorporate throttle valves with mixed refrigerants for the production of cold whereas expander cycle employs compression and expansion equipment with gas-phase refrigerant to produce cold [7]. The liquid air energy storage cycle consists of three main components charging, storage and discharging, which are in fact three physically varied components that can be independently sized. From the charge to the discharge cycles, cryogenic energy is captured, stored and recovered [10].The schematic diagram can be simplified for analysis as shown in Fig. (4).

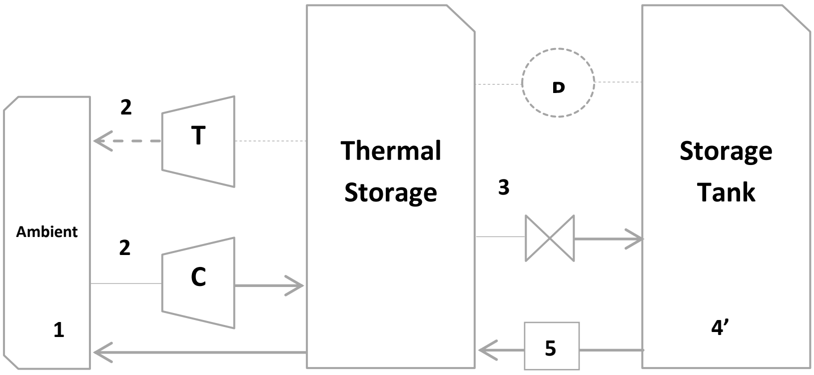


Figure 4: Simplified schematic workflow diagram of LAES

The net-work recycled during compression work “discharging” during charging is known as the round-trip efficiency, which is expressed as [13]

$$\eta = y\frac{(w_t - w_p)}{wc} \tag{2}$$

where: y is the mass of liquid produced/total mass (3-4).
w_t is the turbine work (2-1).
w_p is the pump work (4’-3).
w_c is the compressor work (1-2).

At the commercial scale $(8 - 300MW)$, liquid air technology is capable of having a 60%round-trip efficiency [10]. However, harvesting the waste cold during re-gasification can well enhance the efficiency to 80% [13].If gas compression (1-2) and gas expansion (2-1) are assumed as isothermal process and fluid work behaves as an “ideal gas”, the main loss in the cycle is due to adiabatic work (4’-3), followed by isenthalpic expansion (3-4) loss [10] ,[16]. This results in incomplete work fluid condensation. The inclusion of the cooling work of the cold recovery (2-3) yields;

$$y = \frac{h_1 - h_2 + Q_r}{h_1 - h_l} \tag{3}$$

where: h_1 is the enthalpy at (1).
h_2 is the enthalpy at (2).
h_l is the enthalpy at (4’).
Q_r is the enthalpy recycled during discharge for cold recovery.

$$Q_r = h_2 - (h_1 + W_p) \tag{4}$$

The isothermal work (1-2) and (2-1) can now be determined from the pressure ration, P_r, of the process, gas constant, R, and temperature, T_1:

$$W = R\, T_1\, In P_r \tag{5}$$

Therefore, from Eq. (2) through Eq. (5), η can be determined as a function of a charge/discharge pressure ratio [8], [20].

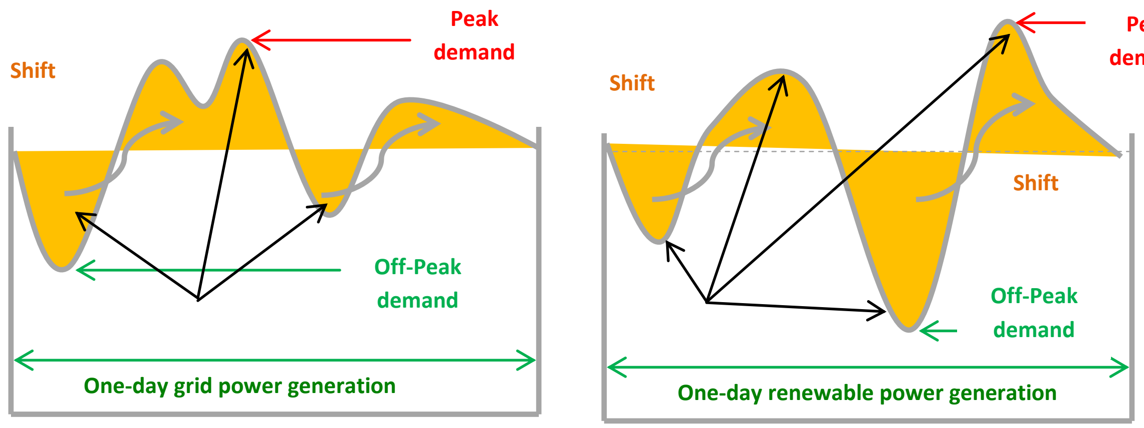
The concept behind the LAES system has been successfully validated at a demonstration plant called the Highview Power Storage Plant in Slough, the UK. In 2008, the Scottish and Southern Energy (SSE) Station hosted the idea of the Highview Power Storage Plant during which time the pilot plant was built on a scale 70 times larger than the $5kW$ lab-scale [10]. The plant was fully commissioned in 2011 with a storage capacity about $300kW/2.5MWh$. In 2014, the Highview Power Storage Plant was awarded £$8M$of funding from the British government to further increase the storage capacity to $5MW/15MWh$. Much of the gas and electricity industry technologies can be transferred to the liquid air system; therefore, the Highview Power Storage Plant is built from mature and widely employed equipment. However, equipment combined in a novel design called a Cryo-Energy System, or Liquid Air Energy Storage system [10]. The system can be divided into three main components – a charging cycle, power storage and discharging cycle. First, excess power from the nearby SSE station is harvested to power the air liquefier (Air Separation Unit) to convert air into liquid. The resulting liquid, which is the energy carrier, is hence stored in the storage tank at -195°C. When the demand at SSE station peaks, the liquid air is obtained from the storage tank and pumped to ambient temperature into a heat exchanger, where the liquid turns back into highly pressurised air. Accordingly, this air is utilised to spin a turbine and electric generator, which supplies the electric power back to the SSE station. The duration for the system to deliver the power back takes only $150sec$, which is promising for applications requiring a fast recovery response [10].

II. LAES Concept Evaluation

I. Energy Storage System for Electric Grid and Renewable Energy

At present, power grids operate in a momentary-time strategy that matches instantaneous supply with instantaneous demand [1]. The global demand for electric power is steadily increasing2% annually, posing a challenge for the power grid to satisfy this ongoing demand. The emanation of the increasing demand is mainly from commercial, industrial and domestic end-users, where demand is constantly changing as a product of time [17]. The penetration of variable generation (renewable energies)exacerbates the momentary-time strategy further because not only do power demands currently fluctuate, but also the power supply. If power demand exceeds power supply, or vice versa, the frequency of this imbalance increases or decreases, causing great instability in the power grid system [18]. Thus, power storage technologies can provide vital opportunities in bridging the future gap between the increased power demand and the power supply. *Power-shifting* and *Time-shifting* are two main opportunities that can decarbonise and secure the future of power energy.

The practice of managing electric power supply and demand so that power during off-peak periods is shifted to power during on-peak periods is the principle behind the power-shifting strategy [22]. On average, power grids operate at a capacity of 40% below their maximum due to on-peak periods lasting only a few hours a day during which time the power grid operates at higher capacities to satisfy the demand [8]. However, if the excess power during off-peak periods is stored and delivered back during on-peak periods, the power grid can exploit its capacity more efficiently. Even if the power demand or on-peak power increase, the power grid does not necessarily increase its capacity to meet only a few hours of demand. Instead, it can use the stored power. Similarly, renewable-based energies can greatly benefit from energy storage technologies where intermittency and unpredictability are met through absorbing excess power when resources are available, (when the sun is shining and wind is blowing), and delivering it back when it is needed,regardless of weather conditions.



(a) (b)

Figure 6: Power generation fluctuations for (a) grid and (b) renewable sources

Fig. (6) exhibits the principle of shifting excess power based on the demand. In Figure (6-a) the pattern illustrates the normal operation for a power grid during a one-day period, while Figure (6-b) illustrates the fluctuation of a renewable power energy operation. It is evident in both cases how a power-shifting strategy can play a major role in the power generation industry, particularly if a great fraction of the power generated derives from renewable energies [22].

The time-shifting strategy is related to the electricity market, rather than to the electric power operation. It allows taking advantage of the benefits of the differences in wholesale electric power prices over the course of a daily period. It is also known as “energy arbitrage”. Power storage systems can be implemented to achieve this strategy via storing electric power when prices are low and releasing it for sale when prices are higher [20]. This reflects the prices during on-peak and off-peak periods. Time-shifting is even more effective in deregulated markets, such as Alberta’s electricity market where prices vary based on the power demand. Likewise, it is mostly beneficial for renewable-based plants where the prices vary as the power demands from the power grid vary [22].

II. Wind Energy in Alberta

Alberta Wind Energy has grown from 563 MW at the end of 2009 to 1088 MW at the end of 2013 and plans to add an additional 1800 MW by 2020. Currently 4% of the power generation within Alberta comes from wind energy, even though 8% of installed capacity is at wind projects. Lifting of the cap placed on wind power has increased the proportion of wind power in the electricity pool. Coal power still dominates power production in Alberta. Wind power can be integrated with viable energy storage systems to increase reliability of wind power and increase flexibility with fluctuating demand. Barriers exist for energy storage systems' widespread adoption. Key barriers to that adoption are competitive cost, validated performance specifications, regulatory uncertainty, industry acceptance [23]. Costs are typically too high for energy storage systems to make them feasible for grid scale application. Especially when we compare the cost of established production methods that compete for the same dollars. Many of the storage technologies have not been around long enough to validate the claims made by the manufacturers. For instance, a battery manufacturer may claim 30 years of high efficiency charging and discharging but if the technology has only been around for 2 years how is that information validated. Another key barrier is regulatory and uncertainty as governments have yet to adapt to these new technologies industry is uncertain of how they will be regulated. This uncertainty prevents adoption. Lastly, industry acceptance prevents widespread adoption of energy storage technology. Industry must have confidence in the products before investing the time and money into these storage technologies. In order for a storage technology to gain widespread adoption it must overcome these main obstacles.

III. Deployment Potential

This suggests the potential benefits for employing power-shifting and time-shifting strategies for the electricity industry in Alberta, Canada through the use of a storage system namely LAES. Alberta Innovates Technology Future (AITF) has already suggested a number of mature storage technologies from which the Alberta electricity industry can incorporate in the future. However, LAES technology was not on the list; therefore, a critical comparison between the listed technologies and LAES technology was conducted in order to exhibit how LAES technology is able to compete.

I. The Liquid Air Energy Storage System for Alberta Wind Energy (Power-shifting)

Coal and gas are currently the main fuels used in Alberta electricity generation, accounting for 82% of its capacity in 2013 [4]. Hydropower has until recently comprised the next source of Alberta's electricity generation capacity, but it is almost surpassed by wind power. Alberta has excellent wind resources, with an over 1,468 $MW$of installed capacity as of Sep. 2014. It is even expected to grow rapidly by1,800 $MW$by 2020 [22]. However, the intermittent nature of wind power exists as an obstacle for its wide penetration into the electricity market in Alberta.

At present, Alberta wind power projects only predict the available wind power to Alberta Electric System Operator (AESO) through a complex forecasting system managed by Alberta Wind Power Forecasting Projects. However, this does not ensure a superior correlation between the forecasted wind power and the actual generated wind power. The use of this forecasting system is somewhat unreliable because a critical difference may occur between the forecasted and actual wind powers upon which the AESO may suffer from system instability and/or the skyrocketing of power prices. A power-shifting strategy can provide a superior penance to mitigate this uncertain challenge through which LAES technology can be deployed. The correlation data between the wind power forecasts received from the Alberta Wind Power Forecasting Projects and the measured "actual" wind power production for the month of January, 2014 are plotted in Fig. (7). Data source is attached in Appendix (A).

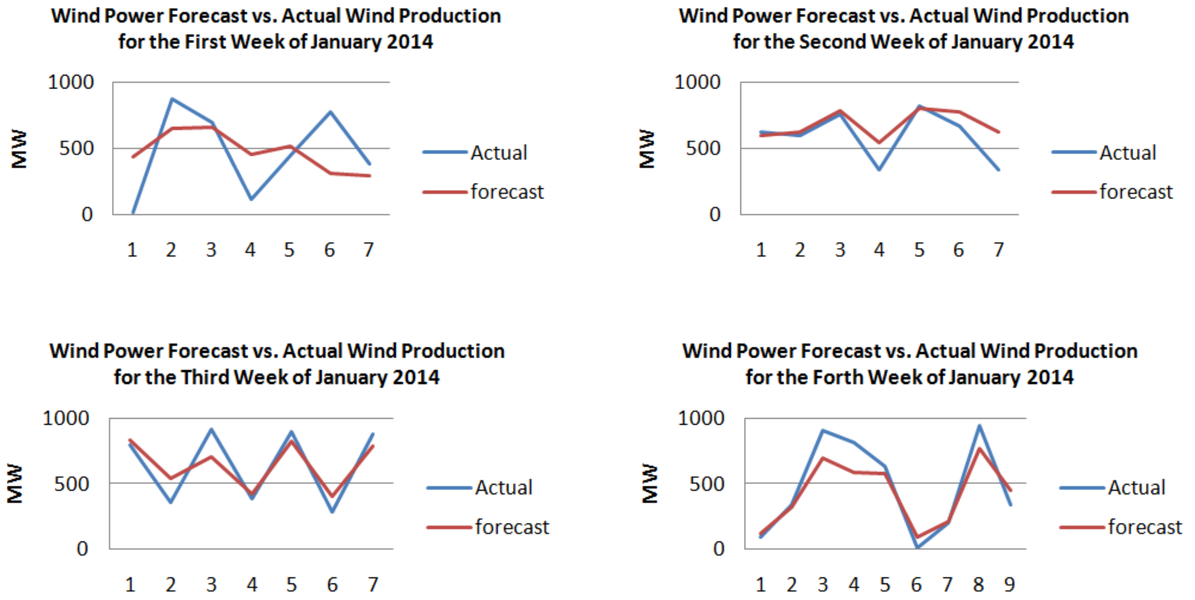


Figure 7: Wind power forecast comparison to actual production for the weeks of January 2014

II. Energy Storage Technologies Compared to LAES Technology

Energy storage technologies in Alberta have been examined in conjunction with wind power production by the AESO and AITF. In collaboration with the AESO, the AITF conducted a study in 2011 on adopting energy storage technologies to support the dispatch of Alberta wind projects. A number of mature storage technologies were suggested for the future of wind power energy in Alberta, discounting LAES. Nonetheless, the maturity of LAES is promising based on the Highview Power Plant know-how. The inherent feature of LAES is summarised in Table (1).

Table 1: Comparison of the most mature energy storage systems to LAES

Technology	Size Range (MW)	Efficiency (Round-trip%)	Geographical Requirement	Maturity
Pumped Hydro (PHS)	> 280	75-85	Mountains/ reservoirs	Commercialised and widely deployed at scales up to a few GW.
Compressed Air (CAES)	Up to 290	45-48	caverns	Demonstrated via two plants in operation up to 290MW.
Sodium Sulphur Batteries (NaS)	< 40	60 experienced for whole system; 80 at cell level	None	Commercialised and most widely deployed battery in stationary applications at scales up to 32MW.
Lead Acid Batteries	Up to 20	65-80 (conventional); 85-90 (advanced)	None	Commercialised in conventional form, deployed up to 20 MW scale; piloted to commercial in advanced form.
LEAS	10 -200	55-85 (depending on thermal waste recycle)	Air	Demonstrated via a pilot plant in operation up to 25MW.

IV. Discussion

I. Liquid Air Energy Storage Systems for Alberta Wind Energy (Power-shifting)

Alberta has energy-only wholesale markets, governed by the AESO whose main responsibility is ensuring the reliability of the electric power supply and establishing an hourly real-time price for electric power. Prices vary with higher prices occurring during on-peak demands. Thus, if the power demand is greater than the available power, the prices for “power generated at that time” increase. In other words, the larger the gap between the power demand and the power supply, the higher the prices and the greater the uncertainty of the AESO. Presently, wind power has attracted serious attention in Alberta, with plans to reach 1,800 MW by 2020; however, this will further exacerbate the uncertainty in the AESO spanning the gap between power demand and power supply. In 2006, the AESO imposed a 900 MW cap on wind power. The cap was lifted in late 2007 after the AESO lunched a wind integration initiative which suggested an energy storage solution to mitigate the intermittency of wind power generation. The wind integration initiative also suggested that the Alberta wind power projects submit firm offers two hours prior to delivering their electric supply. A firm offer that “Must Offer Must Comply” (MOMC rule) adopted by the AESO would challenge the Alberta wind power projects in which they currently only predict the available wind power via a complicated forecasting system. The system uses near real-time meteorological data at wind power sites to indicate the amount of wind power that will be available to the Alberta grid system in the near-term. Although the MOMC rulehas not yet been applied to Alberta wind power projects, they are required to submit a 12-h ahead wind power forecast so that a rough estimate of the available wind power is obtained. Wind power is highly variable, possessing the ability to rapidly ramp up or down and which may be in the opposite direction of load patterns, all of which make predicting wind power and maintaining the reliability of the power system even more challenging.

Alberta wind power projects submit offers based mainly on previously forecasted wind power for which delivery of that amount of power could be a challenge due to wind power variations. However, if an LAES system was installed, offers can be more easily satisfied due to applying a power-shifting strategy. For example, if the actual wind power is greater than the forecasted wind power, the excess can be stored, whereas when the actual wind power is less than the forecasted, the previously stored power can be released, making electric power delivery more reliable. In Fig. (7), the correlation between forecasted wind power and actual wind power was variable. On days 2, 3, 6 and 7, the actual wind power ranged from $900 MW$ to $790 MW$, whereas the forecasted wind power ranged from $630 MW$to$360 MW$. Therefore, the power delivery matched the power that the AESO anticipated to receive. However, on days 1, 4 and 5, the actual power was less than the previously forecasted power in which less power was delivered to the AESO. The AESO now suffers from this uncertainty and needs to promptly bridge the gap between the forecasted and actual wind power. However, this would not be the case if a LAES system was installed because the excess power generated during days 2, 3, 6 and 7 could be stored and then shifted to days 1, 4 and 5 when needed. The schematic operation of LAES technology in supplementing Alberta wind power energy can be depicted in Fig. (8).

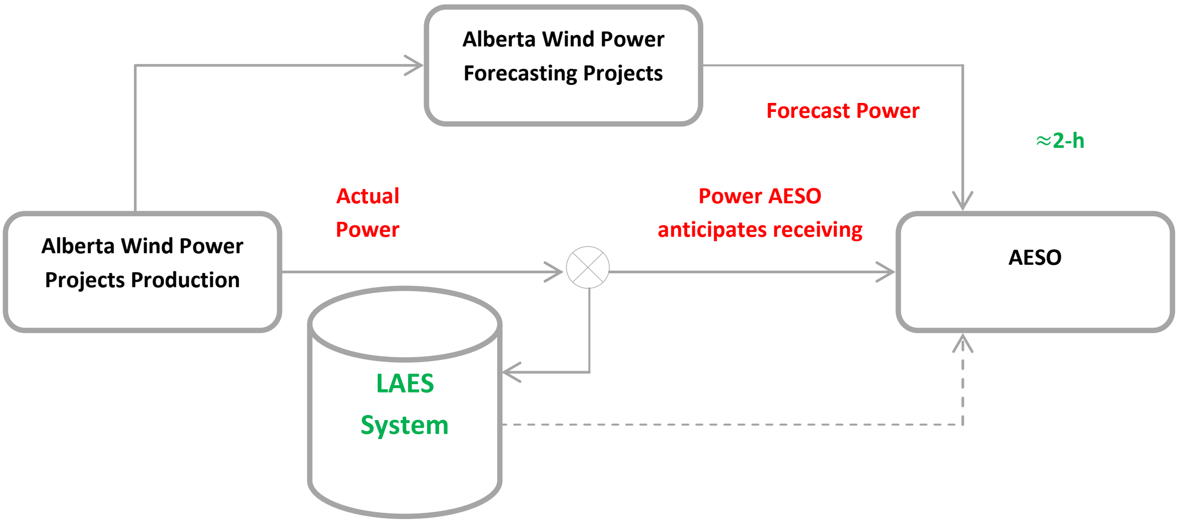


Figure 8: Schematic of LAES integration with wind power

When the actual wind power is less than the forecasted wind power, the difference can be drawn from the power previously stored, whereas when the actual wind power is greater than the forecasted wind power and the AESO cannot absorb the difference (during off-peak periods), the excess power can be then stored (otherwise it is lost). In this regard, wind power projects in Alberta benefit from storing the power generated at the "wrong time" and the AESO benefits from being more certain about the available wind power.

It is clear in Figure (7) that a power-shift strategy will be instrumental for Alberta wind power projects mitigating forecasting system uncertainty. Similarly, for other plots, the forecasted and actual wind powers correlated for some days but not others.

II. The Technical Maturity of Liquid Air Energy Storage Technology

- *The Required Equipment*

Much of the power generation industry, turbo-machinery and gas sectors equipment can be transferred to LAES technology in which all the used equipment is advanced – including compressors, a cold box, and storage medium. This should makeLAES more attractive to Alberta wind power projects compared toNaS and lead acid batteries, which deploy new cells and chemistry techniques requiring long validation periods. Although PHS utilises mature equipment, the hydroelectric nature of the system suffers from the drawback of having long construction times (normally 8-12 years) and requiring large physical land features (mountains). A gas turbine is also a crucial mechanical component in PHS whose operation costsare high because of the use of expensive gas/oil ($\sim 300 g/kWh$). CAES eliminates the gas turbine deficiency in PHS through the employment of a modified gas turbine (turbo-machinery); nevertheless, its usage of a CAES cavern poses a technical challenge. The pressure in a CAES cavern varies during charging and discharging cycles which increases throttle losses between compression and expansion equipment. LAES has the benefit of gas turbine removal and the pressure in the system is independent and can be kept consistent during any operation cycles (charging, storage, discharging). The round-trip efficiency is promising and can be depicted as shown in Fig. (9). It is clear how the round-trip efficiency can be increased with cold-waste recycle.

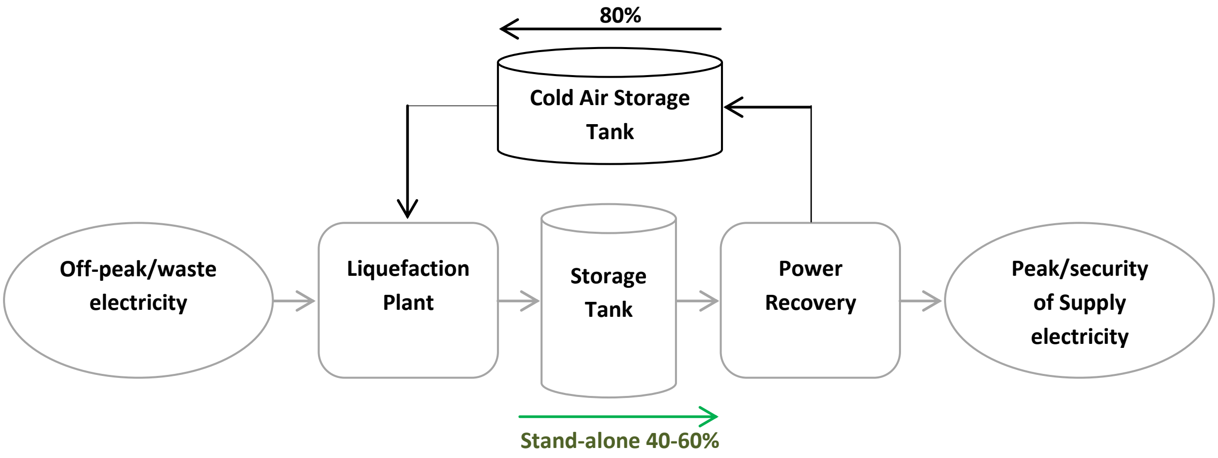


Figure 9: Round-trip efficiency of LAES with and without cold-waste recycle

- *Power Rating and Response Time*

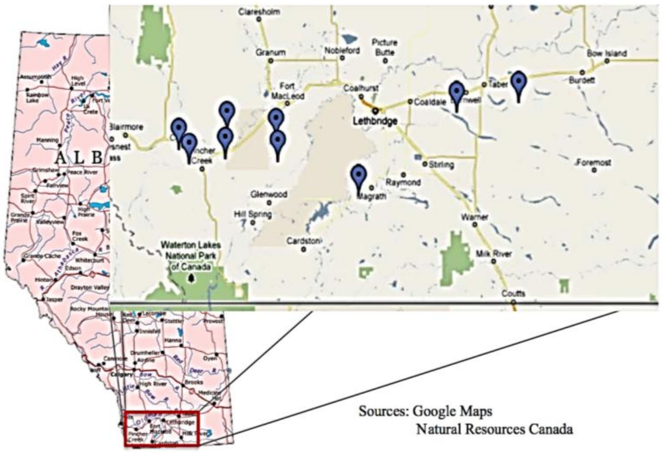
In Alberta wind power projects, PHS, CAES and LAES are more applicable than batteries due to their low power ratings, as shown in Table (1). Thus, batteries are not suitable for large-scale stationary applications. Although PHS and CAES have higher power capabilities than LAES, their response times are inappropriate for Alberta Wind power projects. It is essential that if the forecasted wind power is less than the actual wind power, compensation made promptly to avoid power demands to supply gap issues. LAES technology can be in full operation to supply the stored power in $150 sec$ only.

- *Storage Duration and Self-discharge*

Alberta wind power projects would greatly benefit from a storage system that is capable of storing excess power on an hourly basis. This is because Alberta has energy-only wholesale markets, governed by the AESO whose main responsibility is ensuring the reliability of electric power supply and establishing an hourly real-time price for electric power. Therefore, the AESO requires electric power on an hourly basis. In this case, all the listed technologies in Table (1) are well suitable, except the NaS battery, which has a storage time on a second basis. Self-discharge percentages in all the listed technologies are minimal; nevertheless, LAES technology seems to have the highest self-discharge rate of$0.5 - 1\%$. However, this is not a serious drawback for Alberta wind power projects though, since charging and discharging occur repeatedly based on the gap between forecasted and actual generated wind power.

- *Geographical Requirement*

Most of the wind power projects in Alberta are clustered in the southern region of Alberta, as shown in Fig (10), which lacks mountains for which PHS technology is not applicable. CAES also requires complex underground construction as well as caverns, which are considered geographical limitations. However, LAES technology only requires air and excess power for which it is deployable globally with a minimal footprint and very little restrictions.



Sources: Google Maps
Natural Resources Canada

Figure 10: Map of wind power projects in southern Alb **Natural Resources Canada]**

Two different cases were considered for adoption of LAES technology in the electricity production sector. One case from the perspective of AESO and the other case from the perspective of a wind power electricity producer. Each scenario illustrates different needs that LAES can provide.

III. LAES for Firming Electricity Production

From the perspective of AESO, it is predictable electricity production that is most pivotal for market economics to maintain reasonable production bids. Dealing with fluctuations from renewable energy technologies can present a great challenge for the Alberta System Electricity Operator that must meet the instantaneous electricity demands of consumers. Unexpected outages can create limit the supply of electricity to which pushes bid prices toward the ceiling of $1000/MWh. In 2013, the system marginal price (SMP) exceeded $990/MWh for 53 hours [. These unexpected outages do not come only from wind power facilities but there is a strong negative correlation between high bid prices (over $500/MWh) and wind power production shown implicitly These periods can be very costly for AESO and in turn the province of Alberta.

Use of LAES systems would assist technologies with intermittent production concerns such as wind power to firm up offers to the grid and create better reliability of their electrical production. Table (2) illustrates the annual contribution of wind power in Alberta as compared to the other sources of electricity generation.

Table (2). Pool price range of electricity by fuel type

Pool Price Range MWh	Contribution to Annual Average Pool Price	Coal	Cogen	Gas	Peaker	Hydro	Wind	Other
$0 to $99.99	$27.59	36%	34%	26%	13%	28%	47%	29%
$100 to $149.99	$3.43	4%	4%	4%	4%	4%	4%	4%
$150 to $249.99	$4.76	6%	6%	6%	6%	5%	6%	6%
$250 to $499.99	$10.26	13%	13%	15%	16%	12%	11%	14%
$500 to $899.99	$18.66	23%	24%	25%	32%	24%	21%	26%
$900 to $1000	$15.49	19%	19%	23%	29%	27%	11%	22%
Average Revenue ($/MWh)	$80.19	$77.25	$83.13	$112.18	$213.59	$98.02	$54.97	$95.85

The average load factor of the overall grid producers is 79.4% of the installed 14,568 MW of capacity. However, for the wind power segment of the installed 1,088 MW only generates 31.6% of its load capacity. Wind power consists of 8% of the electricity capacity by nameplate capacity it only generates 4% of the power. Interestingly, during peak hours in 2013 wind power exhibited a capacity factor of 53%. This means that the capacity in off-peak times is dramatically reduced. Capturing this off-peak capacity using LAES would help make the power assets more efficient and ease grid pressures during peak times if the energy was discharged later.

IV. LAES for Arbitrage Opportunities

The advantages of LAES for firming might not be fully appreciated by an electricity producers as their aim is to generate revenue not ensure adequate power supply for the entire province. LAES does present opportunities to increase revenue from the same assets thus increasing their efficiency and the return on the assets. Wind power in Alberta from the perspective of the electricity producer must consider the best methods to yield the most efficient results as it competes in a deregulated market. Perhaps, in a regulated market, electricity producers would not be as concerned with the timing of electricity production but in Alberta the rate that a producer offers can vary greatly as demand fluctuates throughout the day. The ability to meet instantaneous demand can increase the acceptable bid price. In Table 3, the breakdown of the pool price range for wind and other common forms of energy are compared. Wind only generates half of average revenue per MWh because the power it sells is almost half sold at a price ranging between zero and $100/MWh. Wind power has limited control over when the wind blows and so cannot dispatch power that is not generated. And when it does blow it might not be the busier portion of the day so it is sold at a lower value than a peaker plant has the ability to command a higher price because it can meet the peak load demands that the collective baseload facilities do not have capacity to meet. While the peaker plant may be more costly to operate they are able to generate a price/MWh four times that of wind power. LAES would provide an opportunity to store a portion of the energy currently being dispatched at the $0 – 100/MWh range and store the energy until a much greater bid can be offered and accepted.

By shifting a portion of the power generated at off peak times to the higher demand periods similar to yield an average pool price similar to the gas plants or the peaker plants. This strategy will increase revenue by an upper limit of $330 million for the overall wind production within Alberta. If a single wind project (Halkirk) was considered with a capacity of 150MW. Deploying twenty percent of the lower pool price range at peak times may increase revenues at the site by approximately $10,000,000 per annum. This is does not rely on generating any more electricity from the assets only shifting the existing supply to on-peak windows using LAES. Further revenues could be generated depending on the reason for such a low off-peak capacity factor. As stated previously the on-peak capacity factor is 53% percent while the overall capacity factor for wind is 31.6%. If the off-peak is not being exploited because of the minimal returns, LAES could be employed to store the extra wind energy for release. An additional 20% would be a fair assumption yielding another $10 million dollars in revenue for the Halkirk Project. However, if the off-peak reduction in capacity factor is naturally occurring, for instance, wind patterns reduced at night then this additional revenue would not be recognized.

V. Conclusion

Liquid Air Energy Storage Technology demonstrates great potential for delivering reliable and efficient power when partnered with a wind power project. The key barriers of cost competitiveness, validation of performance specifications, uncertainty of regulations and industry acceptance are best overcome by the potential of LAES. LAES uses existing equipment from the cryogenic and power generation industries. This easily bridges the gap between small scale studies, pilot projects and grid-scale operations as equipment for grid-scale capacity have already been in use and the efficiencies and operating costs are known empirically not just theoretically. This is a great advantage over other competing technologies that would require extensive development for grid-scale operations. Utilising existing equipment keeps costs competitive and provides valid performance and safety specifications. All of these factors will encourage industry acceptance. Industry confidence will lead to the greatest adoption of the technology. The only piece still missing is the uncertainty of regulations. If Alberta specifies regulations standards or includes storage technologies in the same category of power generation then industry would be able to plan accordingly. Also, government partnership would entice private industry to develop this technology further.

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Appendix (A)

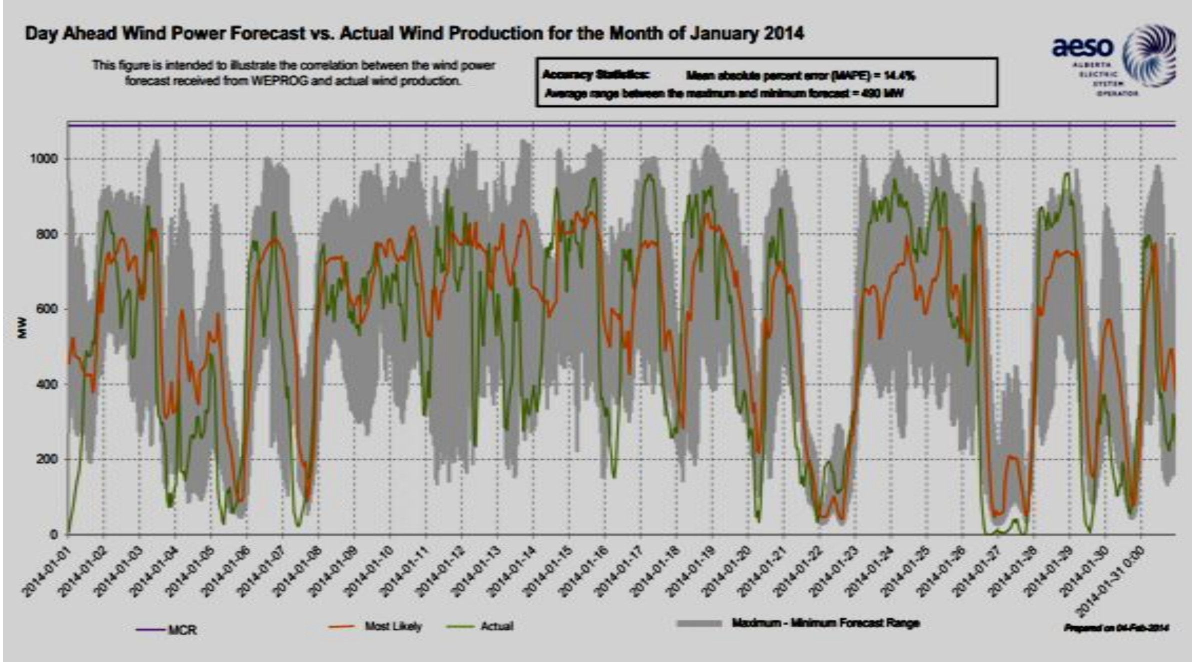

Figure (A) Day ahead wind power forecast obtained from AESO Web-site [2015]

List of Symbols and Acronyms

LAES:	*Liquid Air Energy Storage*
GHG:	*Greenhouse Gas*
ΔE_{total}:	*The total change in energy form*
PHS:	*Pumped-Hydro Storage*
DSM:	*Demand Side Management*
SSM:	*Supply Side Management*
CO_2:	*Carbon-oxide*
MRC:	*Mixed Refrigerant Cycle*
AITF:	*Alberta Innovates Technology Future*
AESO:	*The Alberta Electric System Operator*
MOMC:	*Must Offer Must Comply*
CAES:	*Compressed Air Energy Storage*
SMP:	*The system marginal price*
PEST:	*Political, Economic, Socio and Technical analysis*